UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Summary of Geology and Petroleum Plays Used to Assess Undiscovered Recoverable Petroleum Resources of Sacramento Basin Province, California

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Open-File Report

88-450-O

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TABLE OF CONTENTS

FIGURES

TABLES

INTRODUCTION

During 1987 the Geological Survey conducted an assessment, using a play analysis method, of the undiscovered recoverable petroleum resources of the Sacramento basin province, California, as part of a national assessment (Mast and others, 1988). This report describes the petroleum plays identified for that assessment, and briefly summarizes the geology and petroleum development of the Sacramento basin province.

For the purposes of this assessment, the Sacramento basin province of central and northern California includes the area (1) west of the basement rocks of the Sierra Nevada and Cenozoic volcanic rocks of the southernmost Cascade Range, (2) south of mostly pre-Cretaceous rocks of the Klamath Mountains, (3) east of the thrust fault belt of the Coast and northern Diablo Ranges (which separates Franciscan Formation to the west from latest Jurassic and Cretaceous marine sedimentary rocks of the Great Valley sequence to the east) and, arbitrarily, (4) north of the Stanislaus-San Joaquin county line (fig. 1)[1]. The southwest boundary is drawn to exclude the Livermore and Napa-Sonoma basins (see McLean, 1988, for these basins).

As defined above, the Sacramento province covers about 30,000 km^2 (12,000 mi^2) and contains about 124,000 km^3 (30,000 mi^3) of sedimentary rock (Varnes and Dolton, 1982). Morrison and others (1971) state the province contains about 183,350 km^3 (44,000 mi^3) of sedimentary rock. The Sacramento province is about 323 km (200 mi) long, and averages 72 km (45 mi) wide.

The Sacramento basin, essentially coincident with the Sacramento province, is an elongate, northwest-trending asymmetrical structural trough. This trough is filled with a thick sequence of sedimentary rocks that range in age from Jurassic to Holocene. The entire basin has a southward tilt, and the sedimentary section thickens southward (Hackel, 1966).

GEOLOGICAL SUMMARY

Previous Work

The Sacramento basin is one of the more thoroughly studied basins in the U.S., and many important investigations of its tectonic setting, depositional history and internal structure have been published. Some of the more important studies of broad scope include Goudkoff (1945), Repenning (1960), Lachenbruch (1962), Safonov (1962, 1968), Hackel (1966), Ojakangas (1968), Morrison and others (1971), Dickinson and Rich (1972), Hoffman (1972), Drummond and others (1976), Ingersoll (1978a, 1979), Dickinson and others (1979), Dickinson and Seely (1979), Garcia (1981), Graham (1981), Ingersoll and Dickinson (1981), Cherven (1983a, b), Almgren and Hacker (1984), Harwood (1984), and Harwood and Helley (1987). More areally and topically restricted studies are given in the reference section, including some not cited in this paper. The following geological summary is substantially taken from Dickinson and others (1979), Graham (1981), Cherven (1983b), Almgren (1984), and Harwood and Helley (1987).

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[1]The southern geological limit of the Sacramento basin commonly is defined at the Stockton fault on the northern edge of the Stockton arch (fig. 1). However, gas accumulations and resources south to the Stanislaus-San Joaquin county line are assigned to the Sacramento province in this petroleum assessment.

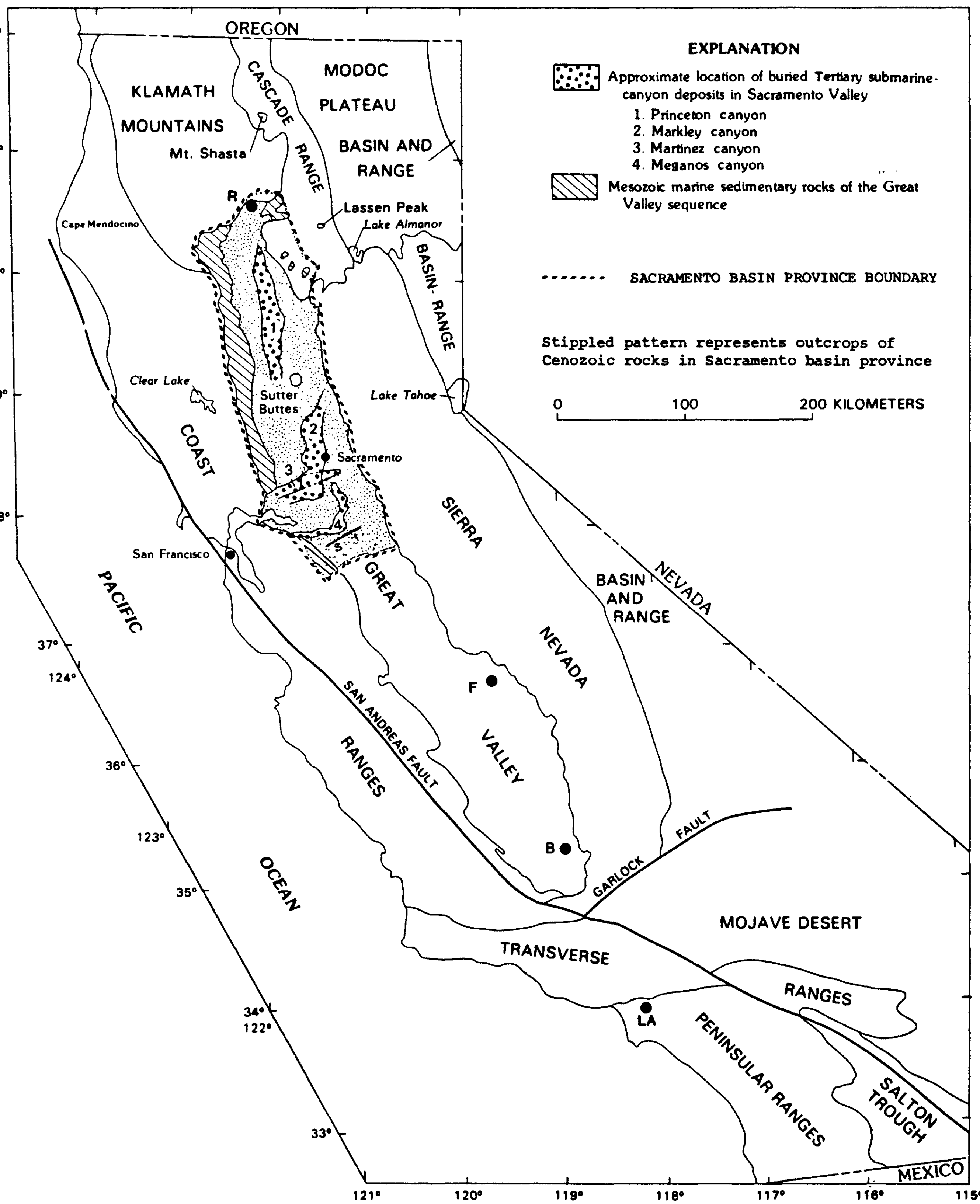

Figure 1. Location of Sacramento basin province, principal California geomorphic provinces, and buried Tertiary submarine canyon deposits. Sf = Stockton fault, R = Redding, F = Fresno, B = Bakersfield, and LA = Los Angeles. Modified from Harwood and Helley (1987).

Tectonic and Depositional History

Late Mesozoic

The Sacramento basin occupies approximately the northern half of the Great Valley of California (fig. 1). During late Mesozoic and early Cenozoic time, the Great Valley was part of an extensive forearc basin developed in a convergent-margin setting by eastward subduction of oceanic crust beneath the western edge of North America (e.g., Dickinson and Seely, 1979). This forearc basin received sediment from the Sierra Nevada arc massif to the east and later also from an archipelago of uplifted subduction complex (Franciscan assemblage) to the west as it evolved from a terraced forearc basin in Late Jurassic to a shelved or "ridged" forearc basin by early Cenozoic (Ingersoll, 1979; Dickinson and Seely, 1979) (fig. 2).

The forearc basin widened through time as the trench-slope break shifted westward and the axis of arc magmatism shifted eastward (fig. 3). The western side of the forearc basin expanded across the accreted subduction complex as a time-transgressive contact between the Franciscan assemblage below and the Great Valley sequence--Late Mesozoic to earliest Cenozoic forearc marine sandstone, siltstone, shale and conglomerate--above (Ingersoll and Dickinson, 1981) (fig. 4A). The eastern side also expanded by depositional onlap and overlap of Great Valley sequence across the eroded flank of the arc terrane due to eustatic sea-level rise during Late Cretaceous and land subsidence (Ingersoll and Dickinson, 1981) (fig. 4C). Probably more than 18,300 m (60,000 ft) of Upper Jurassic to lowest Cenozoic marine sediments--one of the thickest and most complete upper Mesozoic sequences in the world--was deposited in this forearc basin just west of the present west margin of the Sacramento Valley (Hackel, 1966; Graham, 1981). Remnants of this sequence, as young as Campanian (the Forbes Formation), are exposed in the homoclinal outcrop along the west side of the Sacramento Valley (fig. 5). Younger Late Cretaceous rocks (e.g., Winters, Starkey formations) and Paleogene units (e.g., Martinez, Markley, Domengine formations) generally are not exposed in the westside homocline (fig.5).

Because no strata older than Late Cretaceous have been found by drilling above the gently dipping western extension of the Sierra Nevada in the Sacramento Valley, a down-to-the-west hidden fault zone has been postulated to mark the eastern limit of preserved Upper Jurassic and Lower Cretaceous strata in the subsurface (Brown and Rich, 1967; Dickinson and Seely, 1979) (figs. 4B, 5). This postulated fault zone may be the boundary between the subduction complex on the west and basement rocks of the arc terrane on the east (Cady, 1975; Ingersoll and Dickinson, 1981) (fig. 5). Ingersoll and Dickinson (1981) further theorized that this now-buried boundary was a thrust or reverse fault zone that accommodated some degree of crustal contraction across the fore-arc region during "mid" Cretaceous (fig. 2C). They suggested that its northern continuation might be the fault splays that strike northwestward across the north end of the Great Valley homoclinal sequence to join the South Fork Mountain Thrust which separates subduction complex from the Klamath Mountains arc complex (fig. 6). As pointed out by Graham and Ingersoll (1981), resolution of this structural problem may be aided by special seismic experiments designed to examine deeper crustal structure. The answers may provide important information on the origin of some of the gases from the basin (see section entitled Petroleum Source Rocks).

Paleocurrent indicators in westside exposures of Upper Jurassic and Lower Cretaceous turbidites indicate southerly flow parallel to the continental margin and suggest the presence of a bathymetric barrier to the west that deflected sediment to the south (e.g., Ingersoll, 1979). While basin-plain and outer-fan facies are present along most of the western outcrop belt, slope deposits and, locally, shelf deposits at the northern end evidently reflect shoaling of the forearc trough toward the north against the Klamath Mountains block (Ingersoll and Dickinson, 1981). Upper

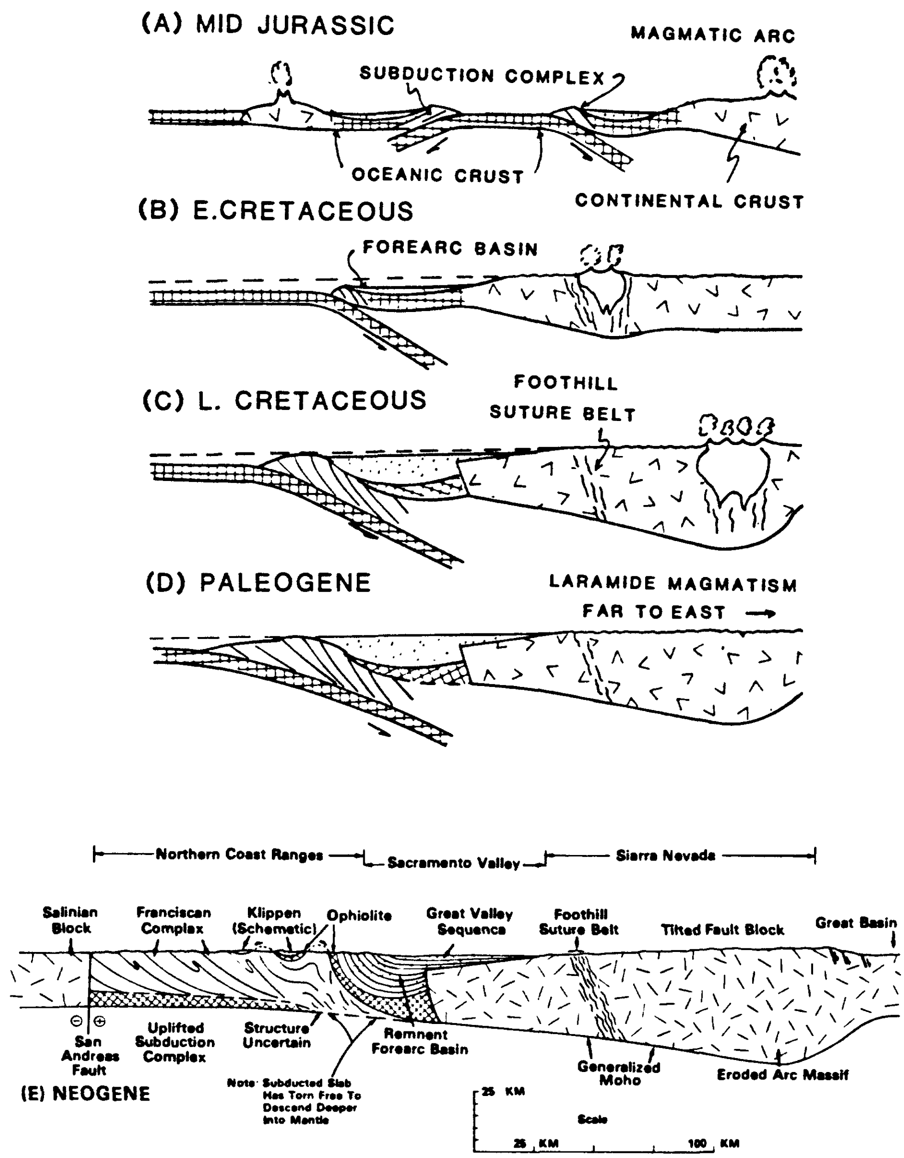

Figure 2. Evolutionary stages of the history of the arc-trench system of California from Jurassic (A) to Neogene (E). (A) through (D) modified by Cherven (1983b) from Dickinson and Seely (1979) and Graham and Ingersoll (1981). (E) is from Dickinson and Seely (1979). Each diagram depicts conditions at end of time span indicated and structural telescoping is depicted here arbitrarily as discrete mid-Cretaceous event, but doubtless took place over some finite part of Cretaceous time (Dickinson and Seely, 1979).

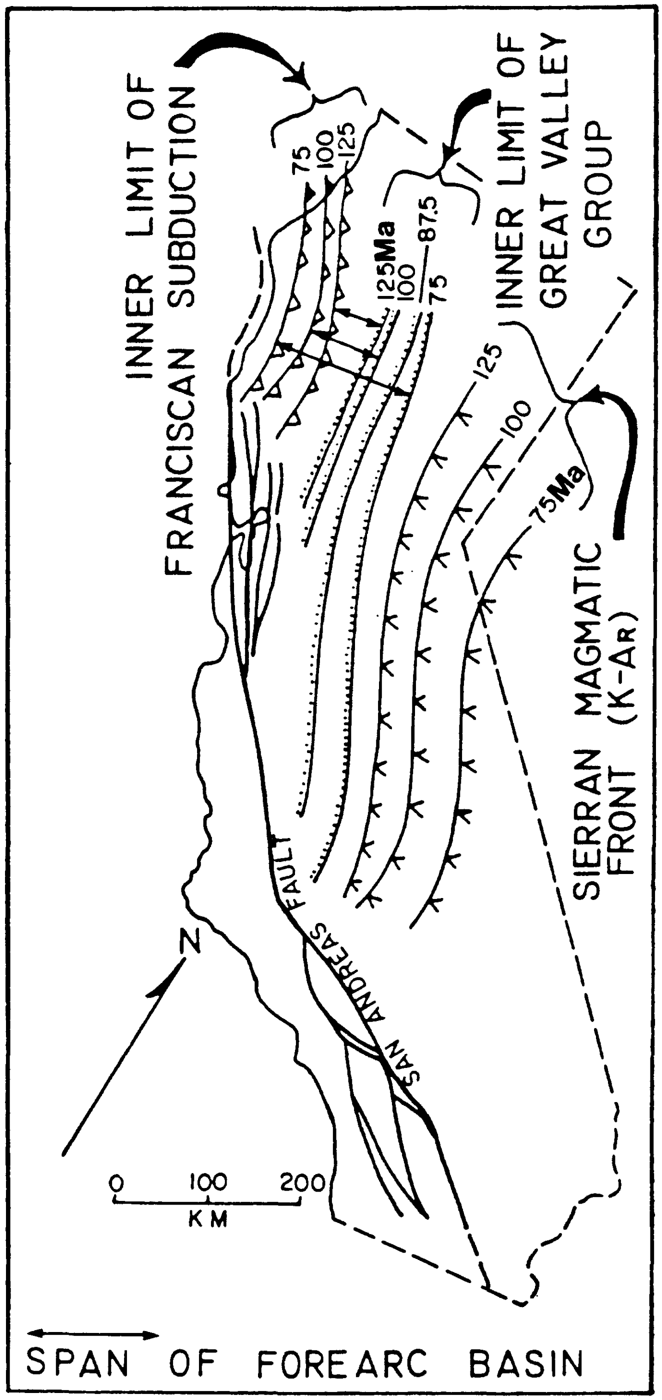

Figure 3. Schematic map illustrating the progressive increase in the width and eastward onlap of the Great Valley forearc basin from Early Cretaceous (125 Ma) to Late Cretaceous (75 Ma) (figure and caption from Ingersoll and others, 1977). Positions of western boundary at migratory trench-slope break marking inner limit of active subduction are inferred from easternmost extent of successively younger strata within the Franciscan complex. Positions of eastern boundary at migratory shoreline mark easternmost extent of successively younger strata present in subsurface of modern Great Valley. Positions of the magmatic front marking western limit of igneous belt are inferred from westernmost limits of radiometric dates for Sierra Nevada plutons (Evernden and Kistler, 1970).

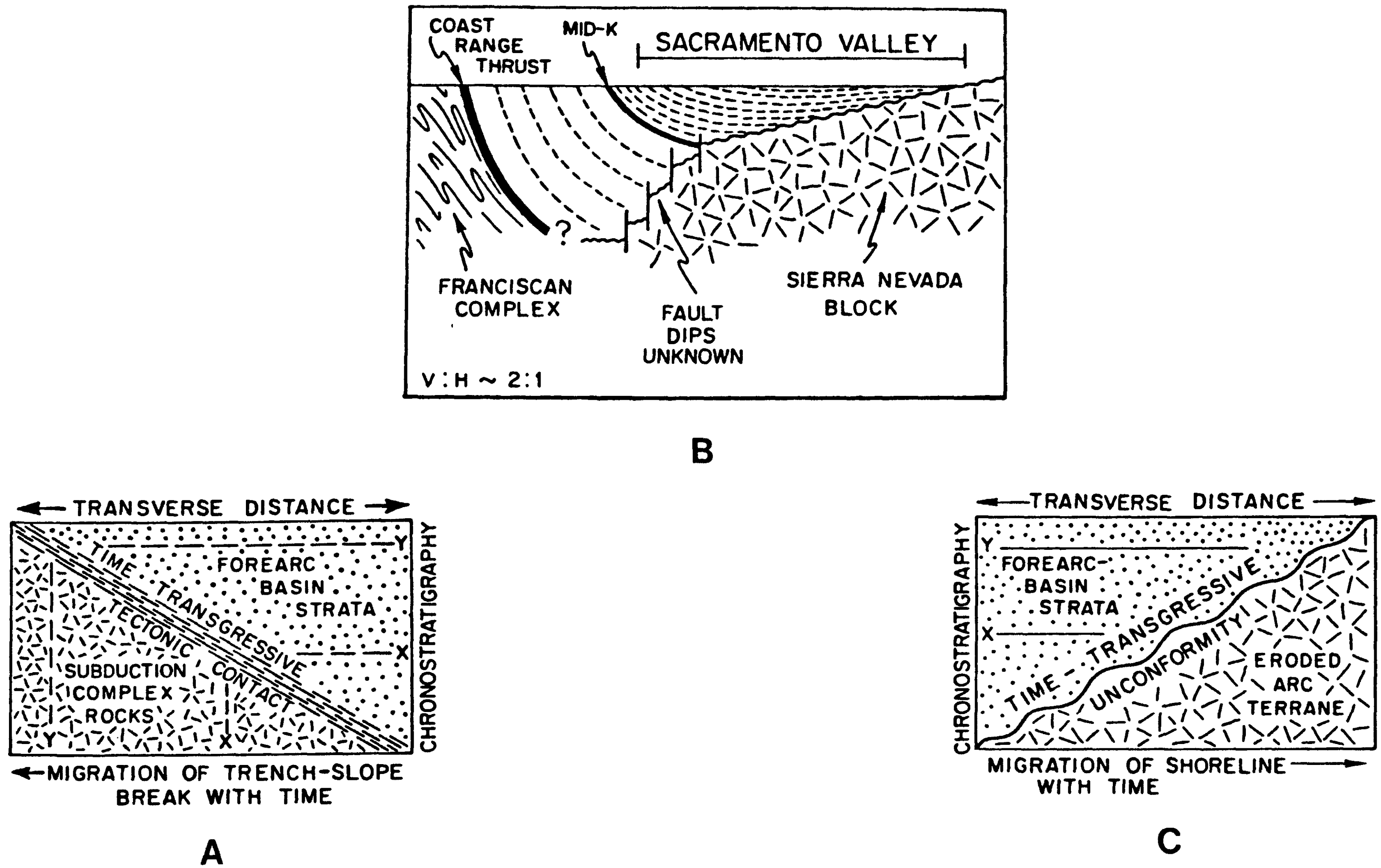

Figure 4. Schematic diagrams of inferred development of western (left) and eastern (right) flanks of late Mesozoic forearc basin (Ingersoll and Dickinson, 1981). The tectonic contact (left) and depositional contact (right) both indicate transgression that led to widening of the forearc basin during late Mesozoic. Center figure shows postulated faulting on eastern flank to account for abrupt loss of thick Great Valley sequence strata from west to east across present-day Sacramento basin (Ingersoll and Dickinson, 1981).

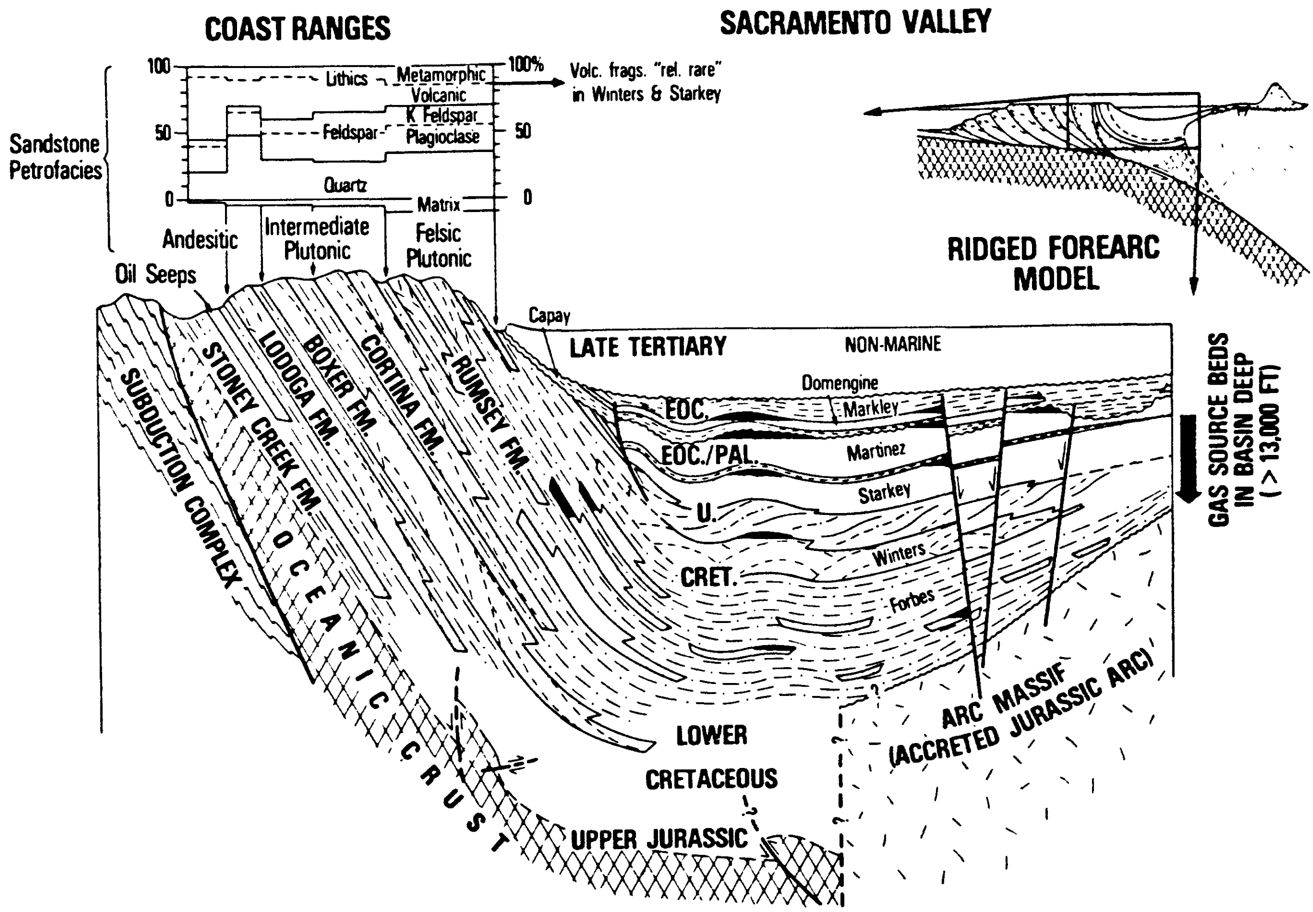

Figure 5. Schematic cross-sectional structure and stratigraphy of the Sacramento Valley (figure and caption from Dickinson and Seely, 1979). Outcrop sandstone petrofacies are from Ingersoll and others (1977). Volcanic content of Winters and Starkey and progradation between them are from Drummond and others (1976). Structural and stratigraphic positions of gas occurrence (black areas) are from T. P. Harding (personal communication, 1977). Stratigraphic and structural relations are not to scale. Thrusting of oceanic crust on subduction complex (left side of diagram) occurred after deposition of Great Valley sequence in Cretaceous forearc basin.

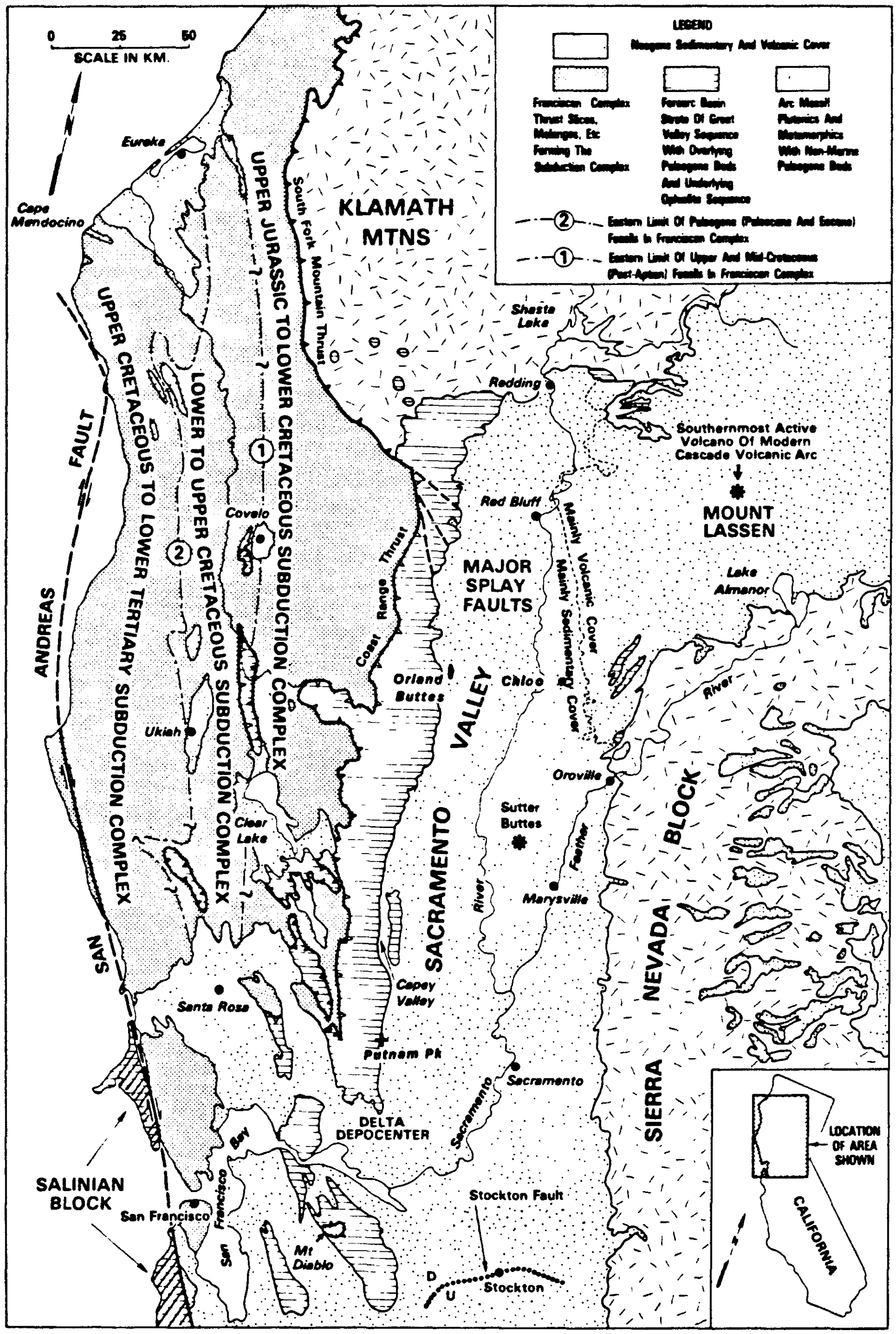

Figure 6. Generalized geologic map of part of northern California showing structural relations of strata deposited in late Mesozoic and early Cenozoic forearc basin of Sacramento Valley and adjacent uplands of northern Coast Ranges on west (slightly modified after Dickinson and Seely, 1979). Also shown are the Stockton fault, Delta depocenter, Putnam Peak, Orland Buttes, and Sutter Buttes.

Cretaceous strata in westside exposures are largely slope and fan deposits that display southwesterly to southerly paleocurrents (Ingersoll, 1978b, 1979).

Subsurface studies of Campanian and Maastrichtian fluvial-deltaic, slope and deep-sea fan depositional systems are best documented by Drummond and others (1976), Garcia (1981) and Cherven (1983a). Garcia's interpretation of the Campanian Kione delta in the northern Sacramento basin is shown in Figure 7. The high constructive Kione deltaic system overlies and in part interfingers westward and southwestward with basinal or mid-fan Forbes sandstone and shale deposited during the Campanian transgression (Graham, 1981). Cherven's schematic interpretation and cross section of the depositional relationships of the Campanian Lathrop fan and Maastrichtian Starkey delta system, and Winters and Tracy fan systems in the southern Sacramento basin, are shown in Figures 8 and 9. The Lathrop and most of the Winters fan systems were developed from an eastern, north-south-trending depositional slope. Later, after extensive progradation of the delta systems and basin filling, the Tracy fan system developed primarily from an east-west-trending, south-facing depositional slope that eventually extended deposition into the northern San Joaquin province (Cherven, 1983a). The Kione delta system, Forbes basinal or mid-fan sandstones and Starkey-Winters depositional system contain the principal gas reservoirs of Cretaceous age in the Sacramento basin.

The general north-to-south shoaling during Campanian and Maastrichtian included intermittent transgressive periods (e.g., transgressive Delta and Sacramento shales of local usage) and broad uplift and tilting of the basin to the south and west (Cherven, 1983b, Safonov, 1962). By the end of Cretaceous, the deltaic and fluvial Mokelumne River Formation was being deposited in the Delta depocenter (fig. 6), while subaerial erosion was widespread elsewhere in the basin (Dickinson and others, 1979).

Sediment source materials evolved along with the late Mesozoic forearc basin (e.g., Ingersoll, 1981). Ingersoll and others (1977) developed sandstone petrofacies in the westside exposures of the Great Valley sequence from which sandstone provenance was shown to evolve from andesitic (Stoney Creek Fm.) through intermediate plutonic and volcanic (Lodoga, Boxer, Cortina Fms.) to felsic plutonic (Rumsey Fm.) (fig. 5), apparently as magmatic arc volcanism gradually declined and the volcanic cover was eroded to expose batholithic rocks (Dickinson and Rich, 1972). This evolution of sandstone provenance was particularly favorable for the development of better petroleum reservoir rocks in the younger sandstones of the forearc basin that contain higher percentages of stable framework grains (fig. 10; also see section entitled Diagenesis of Petroleum Reservoir Rocks).

Early Cenozoic

The Sacramento basin remained a forearc basin during Paleogene time and was characterized by slope, shelf and nonmarine depositional environments with intervening periods of subaerial erosion until the last marine regression during Oligocene time (Hackel, 1966). The cutting and filling of four large submarine canyon systems also occurred during the Paleogene (e.g., Almgren and Hacker, 1984) and increased tectonic activity commenced, principally in the southern part of the basin.

The following summary of the Paleogene depositional history of the main part of the Sacramento basin (excluding submarine canyon development which is discussed in later paragraphs) is slightly modified from Dickinson and others (1979, table 2).

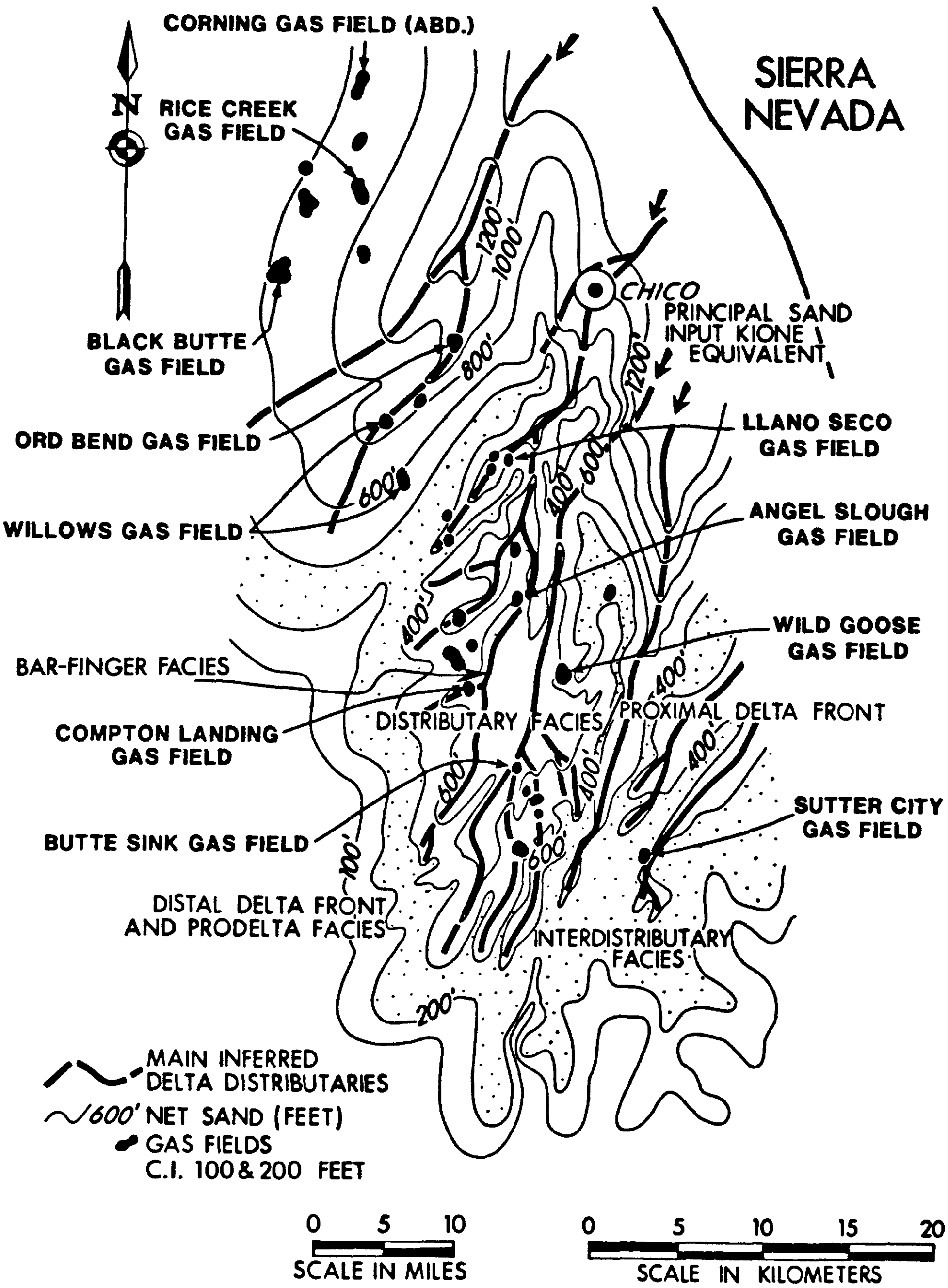

Figure 7. Depositional system of the Campanian Kione delta of northern Sacramento basin showing net sand thickness, inferred depositional facies with main delta distributaries, and discovered gas reservoirs of Kione sandstone (figure and caption from Garcia, 1981).

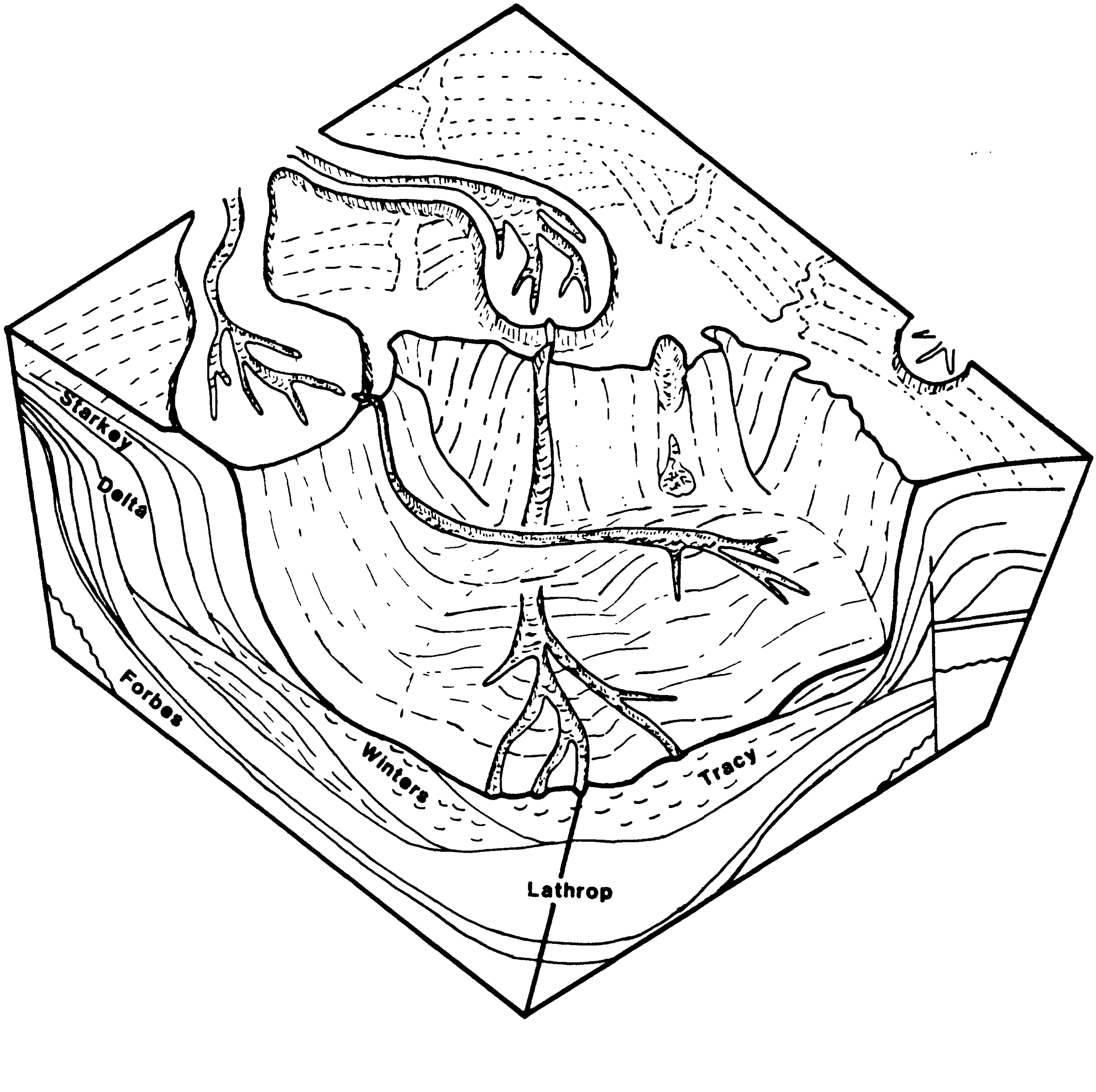

Figure 8. Oblique view to northeast from northern San Joaquin basin into southern Sacramento basin, showing genetic relations of deltaic, slope and submarine fan systems to which Maastrichtian Lathrop, Starkey-Winters and Tracy sands (of local usage) belong (figure and caption from Cherven, 1983a). Early generation of wave-dominated deltas (symbolized by dashed lines representing accretionary beach ridges) is related to Winters submarine fan deposits and lower part of Delta shale. Later generation of fluvial-dominated deltas at shelf edge is shown spilling sand through slope channels to two lobes of Tracy fan. Delta switching has caused recent abandonment of delta in middle and progradation of delta at left. Hence, fan lobe at right has partly overlapped lobe in center and built into depression lateral to abandoned lobe (Cherven, 1983a).

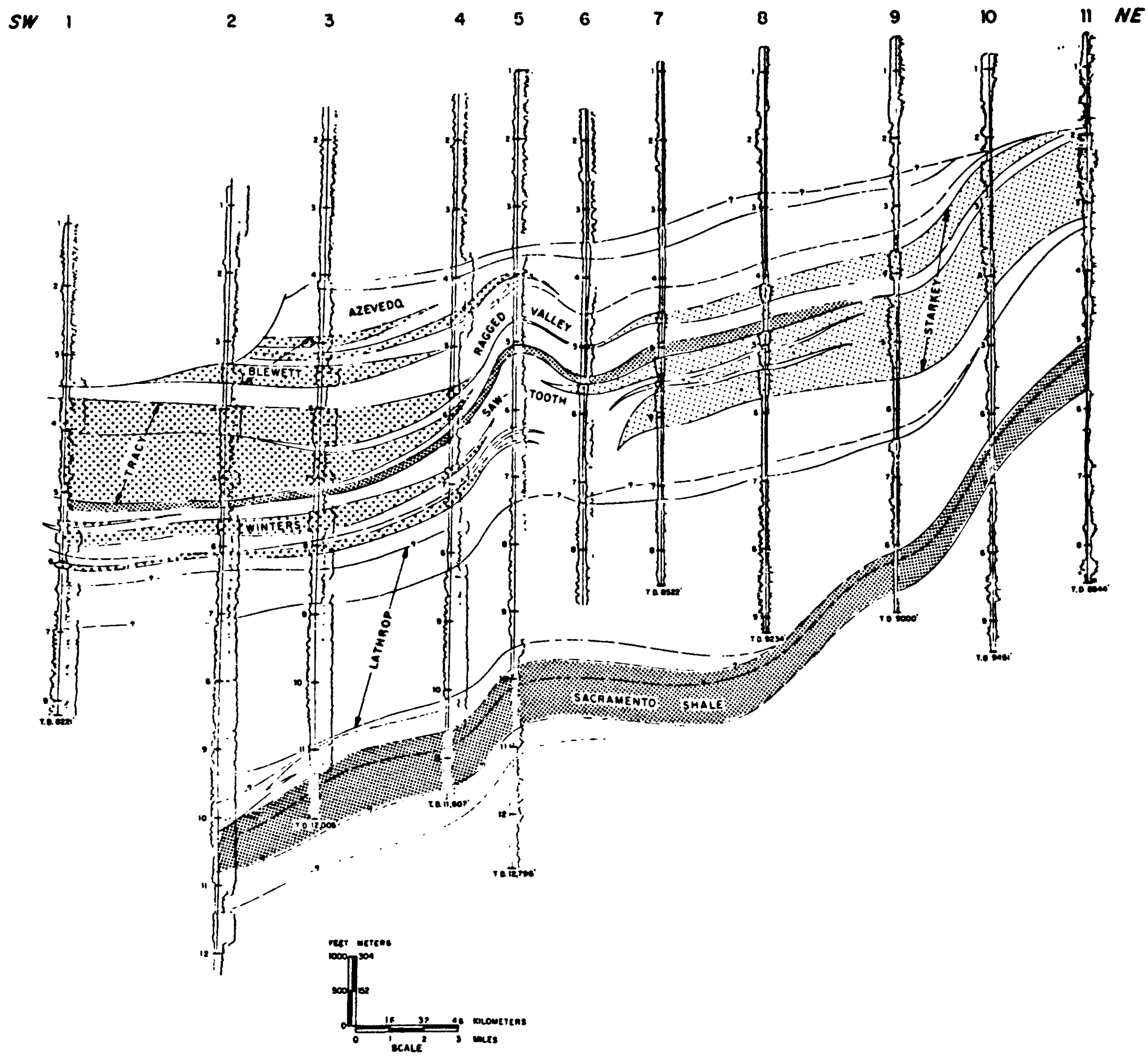

Figure 9. Southwest-northeast cross section across the southern Sacramento province (Cherven, 1983a) (see fig. 16 for location). The prodelta facies of the Starkey thickens westward from pinch-out near well 9 and grades to slope shale at well 7. Thin sand beds in wells 5 and 6 are slope channels connecting to submarine fans to southwest. Structural high at well 5 is Lathrop anticline. Fine dot pattern is shale; coarse dot pattern is sand. Unpatterned section represents marine sand-shale sequences not interpreted by Cherven (1983a).

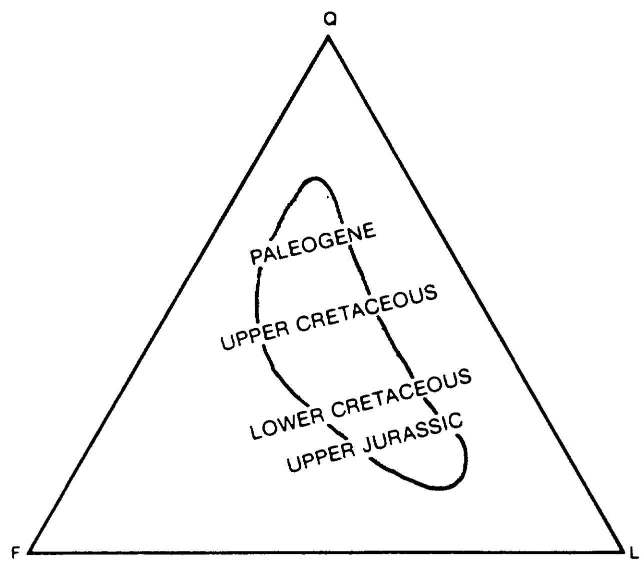

Figure 10. General petrofacies trend with decreasing age toward quartz enrichment and lithic fragment diminution in detrital modes of Sacramento basin sandstones. Stippled area encompasses mean compositions of petrofacies of Intersoll (1981) and Paleogene sandstone compositions reported by Dickinson and others (1979). O = framework quartz grains, F = framework feldspar grains, L = framework lithic grains (figure and caption after Graham and Ingersoll, 1981).

Early Paleocene: Maximum regression developed widespread subaerial unconformities except within parts of the Delta depocenter.

Late Paleocene: During renewed transgression, shallow-marine sandstones and shales of the Martinez and Meganos formations were deposited within the Delta depocenter to a maximum thickness of about 1,500 m (4,920 ft) near Mount Diablo (fig. 6).

Early Eocene: Continued transgression spread neritic shales of the Capay Formation generally to a thickness of about 50 to 100 m (164 to 328 ft), as a thin shelf deposit across most of the basin. The Capay is conformable or at least concordant with underlying Paleocene rocks in the Delta depocenter but elsewhere rests unconformably or disconformably on various underlying units (Safonov, 1968; Redwine, 1972).

Early to Middle Eocene: Progradational shoreline deposits of the Domengine Formation (~250 m or 820 ft in thickness) mostly are conformable but locally unconformable on underlying strata. The Domengine deltaic system prograded fully across the basin to the Delta depocenter (Graham, 1981), but upper Domengine reflects renewed marine transgression (Cherven, 1983d).

Middle Eocene: Shales of the Markley Formation deposited in deep marine slope environments are similar to and age equivalents of those in the Kreyenhagen Formation in the San Joaquin basin except for the presence of interbedded turbidite sandstones--the Markley Sandstone member. Thickest sections of the Markley Formation with an aggregate thickness of about 1,250 m (4,100 ft) generally are confined to the western part of the Delta depocenter. Outside the Delta depocenter, the Markley Formation is truncated by post-Eocene unconformities (Nilsen and Clarke, 1975).

Late Eocene-Oligocene: Hiatus related to widespread regression extends throughout the Sacramento basin. Neogene sedimentation was entirely nonmarine except in parts of the San Francisco Bay area. Contacts between Paleogene marine and Neogene nonmarine strata are everywhere unconformable in the basin (Hackel, 1966).

Four subsurface Paleogene submarine canyon or valley systems have been recognized and described in the Sacramento basin (Almgren and Hacker, 1984) (fig. 11). These submarine canyons (sometimes called gorges) were cut and filled during periods of marine regression and transgression due to regional uplift, tilting and(or) eustatic sea-level changes. Pertinent facts about these ancient submarine canyons are listed in Table 1. Isochore maps and a representative cross section that illustrates the Martinez, Meganos and Markley canyons are shown in Figures 12 and 13. The stratigraphic position of the fill in these three southerly canyons is shown in Figure 14.

The cutting and subsequent (mostly subaqueous) filling of each Paleogene canyon was followed by deposition of a transgressive-regressive marine sequence (Almgren, 1984) (fig. 13). Almgren (1984) identified three complete transgressive-regressive cycles and a fourth that was interrupted by the final emergence of the basin during Oligocene. The approximate area of the last extensive transgressive cycle, during which the Early Eocene Capay formation was deposited, is shown in Figure 15.

The Martinez, Meganos, Princeton and Markley submarine canyons are filled mostly with low-permeability marine mudstone and shale that played a very important role in the entrapment of gas in Sacramento basin (see section entitled Reservoir Trap Types). The discovery and characterization of these canyons is the result of decades of drilling, geophysical surveys and painstaking study by many explorationists in the petroleum industry (Almgren and Hacker, 1984).

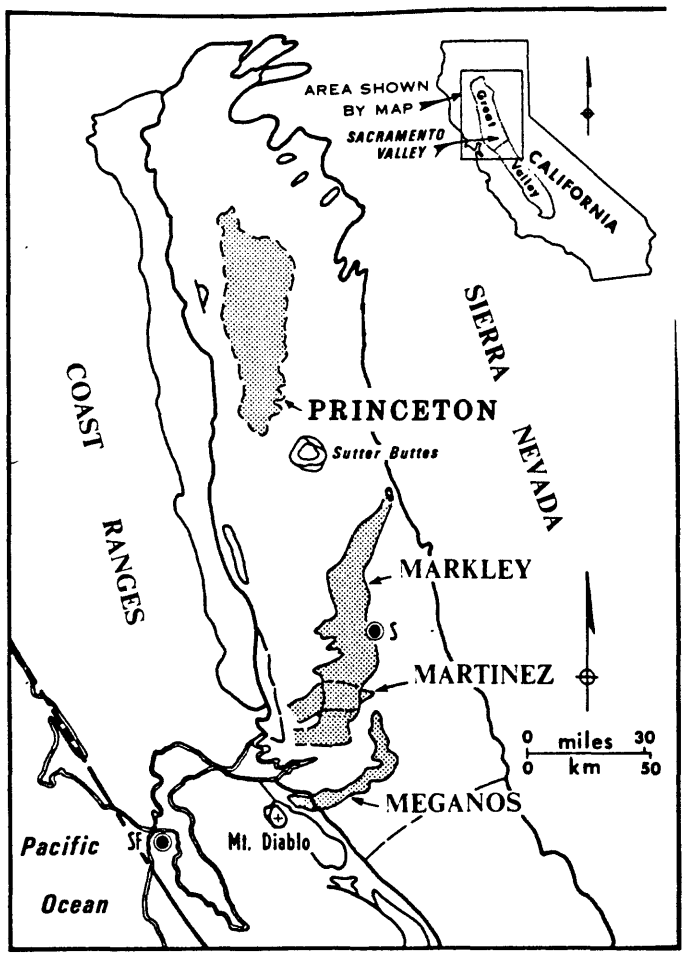

Figure 11. Locations of Martinez, Meganos, Princeton and Markley Paleogene canyons, Mt. Diablo and Sutter Buttes in Sacramento basin, California. S = Sacramento, SF = San Francisco. (from Almgren, 1984).

Table 1. Parameters of Paleogene submarine canyon or valley systems, in Sacramento basin, California (modified from Dickinson and others, 1979).

Parameter:	Description	Meganos Gorge	Markley Gorge	Princeton Gorge	Martinez Gorge[a]
Length (km):	includes over-all canyon curvature but not local valley or thalweg meanders	70	125	225 (min) 275 (max)	32
Width (km):	transverse distance from rim to rim	5-12 (avg: 8-9)	15 (max)	10-15 (avg?) 35? (max)	12
Depth (m):	maximum distance from rim to floor as inferred from subsurface thickness	750	750-1,000	750-1,000	365-400
Side slopes (degrees):	restored values with structure removed	5-15	5-25	7.5?	-
Axial slope (inferred):	maximum depth divided by length	0.011	0.007	0.004	0.012
Stratal floor:	oldest strata into which thalweg is incised	Maastrichtian	Campanian	Santonian/ Coniacian	Campanian
Stratal rim:	youngest flanking strata covered by draped fill	Upper Paleocene	Upper Eocene[b]	Upper Paleocene	upper Lower Paleocene
Strata fill:	age of strata that fill the canyon	Early Eocene[b]	Early Oligocene[b]	Early Eocene	early Late Paleocene

Note: Original Dickinson and others (1979) table adapted from Almgren and Schlax (1957), Safonov (1962), Edmondson (1965), Dickas and Payne (1967), Redwine (1972), Baker (1975), and Rodney Nahama and F. E. Weagant (1972, oral communication).

[a]Martinez gorge data from Almgren and Hacker (1984)
[b]Ages from Almgren (1984) and Almgren and Filewicz (1984)

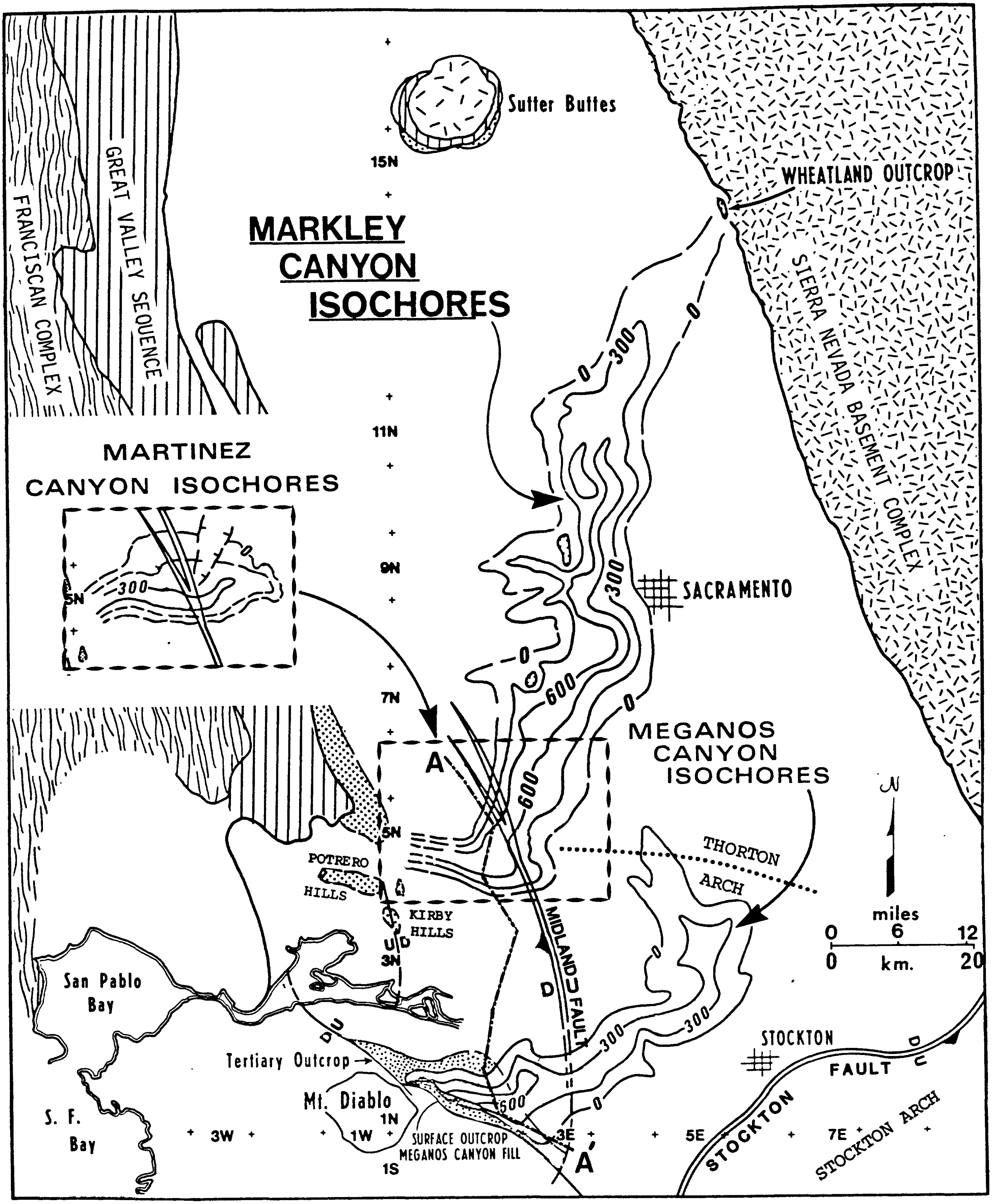

Figure 12. Map of southern Sacramento basin showing isochores (in meters) of fill in Martinez, Meganos and Markley submarine canyons of Paleogene age (adapted from Almgren, 1984). Inset shows isochores of Martinez canyon with arrow to framed location on map. Cross section AA' (fig. 13) also is shown. Exposures of Sierra Nevada basement complex, Great Valley sequence, Franciscan Formation, and Tertiary are shown by pattern. Wheatland Formation outcrop is believed to represent fill of the Markley canyon.

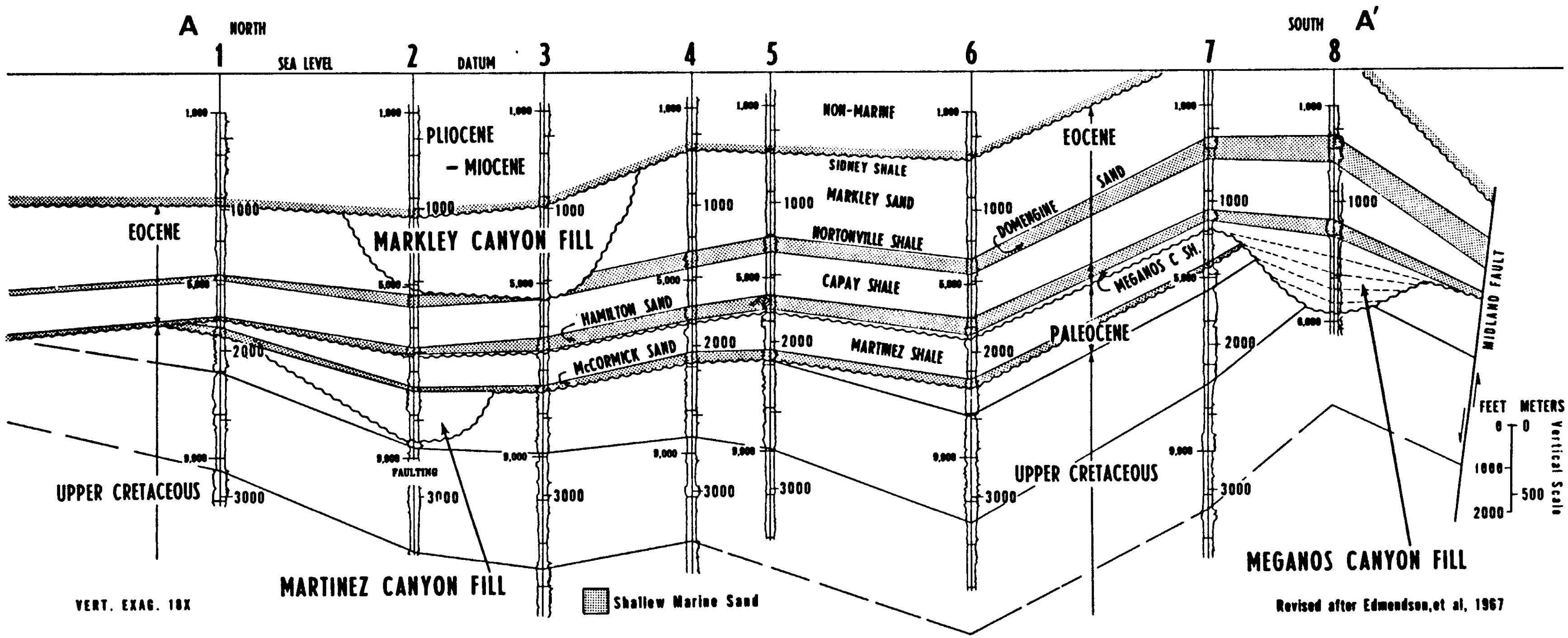

Figure 13. Stratigraphic cross-section A A' showing relationship of Tertiary canyon fills to associated cycles of sedimentation (figure and caption from Almgren, 1984). Location of cross-section A A' is given on Figure 12.

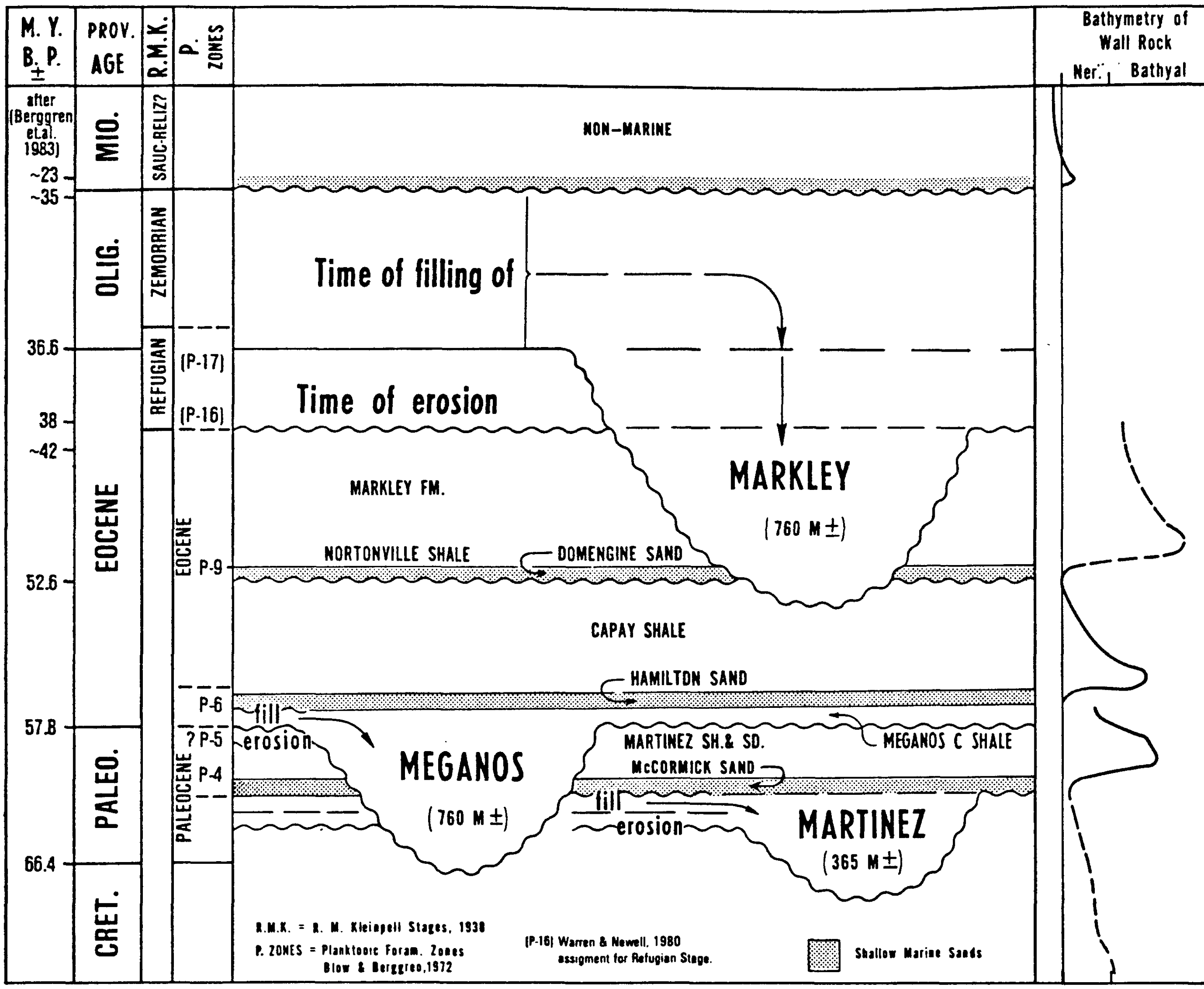

Figure 14. Schematic chart showing relationship of three Paleogene submarine canyons in the southern Sacramento basin to periods of erosion and deposition (after Almgren, 1984). Suggested absolute ages and positions of planktonic foraminiferal zones are tentative. Princeton submarine canyon in northern Sacramento basin occupies position identical to that of the Meganos canyon except that Capay Shale most widely overlies its fill. See Cherven (1983b) for slightly different age and bathymetry assignments. Maximum thickness of canyon fill is given in meters.

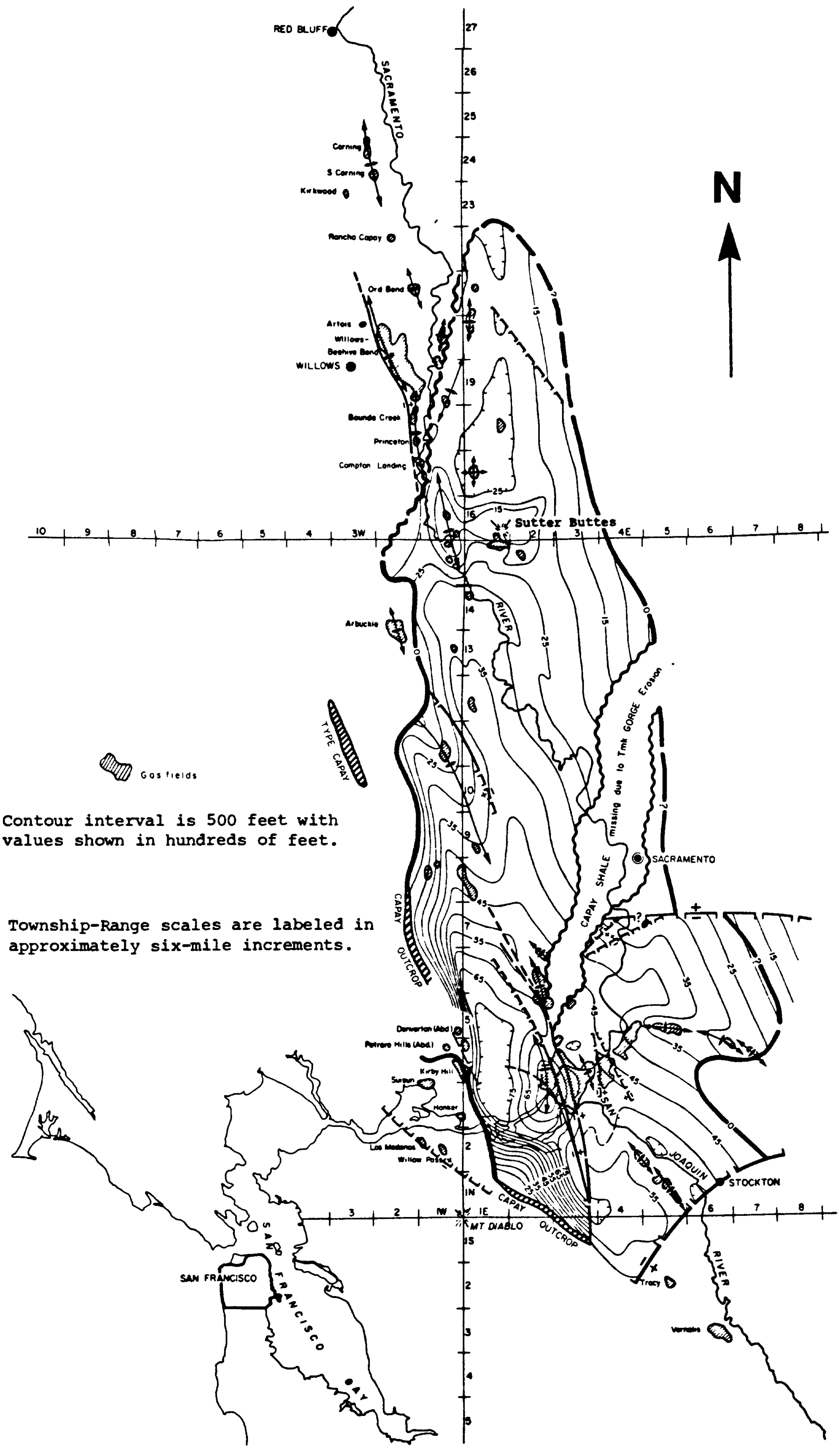

Figure 15. Structure contour map on base of early Eocene Capay shale in the Sacramento basin (Safonov, 1968). Contour interval is 152 m (500 ft). Capay outcrops and some gas fields, cities and faults also are shown.

Late Cenozoic

Neogene to Recent sedimentary rocks in the Sacramento province everywhere are nonmarine and unconformably overlie Paleogene marine rocks, except around the eastern margins of the San Francisco-San Pablo Bay area where marine rocks of Miocene age occur locally (Hackel, 1966; Graham and others, 1981).

The Lovejoy Basalt, dated between 23.8 and 22.3 Ma (Dalrymple, 1964), was erupted from vents in the northern Sierra Nevada (Durrell, 1959) and is present in many wells drilled in the central and eastern parts of the northern Sacramento basin (van den Berge, 1968; Redwine, 1984) where it has been used as a time line for later basin deformation by Harwood and Helley (1987). The Miocene "upper Princeton Valley fill" was deposited in the northern part of the basin in a north-south-trending erosional valley that was broader and less distinct than its Paleogene predecessor (Redwine, 1972, 1984).

Other Miocene and younger nonmarine sequences include the Miocene Valley Springs and Mio-Pliocene Mehrten Formations at the south end of the basin, and the Pliocene Tehama and Tuscan Formations in the northern area of the basin. None of these rocks have been extensively studied in the subsurface.

Structural History

The Cretaceous and much of the Tertiary tectonic history of the Sacramento basin province was dominated by the presence of a subduction zone along the continental margin to the west that imposed a general east-west compressive stress regime. Broad and gently disharmonic folding in the westside outcrop belt of Great Valley sequence were believed by Dickinson and Rich (1972) to reflect mid-Cretaceous flexuring of the northern basin floor. However, factual subsurface information about pre-Late Cretaceous deformation seems to be lacking because these rocks generally have not been extensively tested by drilling.

Oblique subduction with a northerly to northeasterly convergence direction, during Late Cretaceous and early Tertiary (Engebretson and others, 1985), apparently produced a north-south compressive stress and a right-lateral shear couple in the western part of the continent in the early Paleogene (Page and Engebretson, 1984) or latest Cretaceous. The effects of this different stress regime were greatest principally in the southern part of the Sacramento province and probably initiated such major features as the Stockton arch, Stockton fault zone, Thornton arch, Midland fault zone, localized subsidence in the Delta depocenter and the routes of the southernmost Paleogene submarine canyons. (See isopach map and cross sections in Figures 16, 17, 18, and 19.) The intermittent southward and westward tilting of the Sacramento basin since latest Cretaceous time (Safonov, 1968), evident in Figures 17 and 18 (cross section C), may be due in part to this different stress regime.

The Stockton arch (figs. 12 and 17), thought by Bartow (1987b) to be a simple south-side-up, tilted fault block, formed during latest Cretaceous or early Paleocene at the south end of the province. The Stockton arch is evident as an area where Paleogene and uppermost Cretaceous Great Valley strata have been truncated beneath Neogene strata (Hoots and others, 1954). There is little evidence of arching in overlying Tertiary units (Bartow, 1985), and no evidence of basement arching (Bartow, 1983). The structure existed as a low-relief positive feature through most of the Paleogene and experienced a major period of uplift in the Oligocene. Presumably the Stockton arch formed in response to north-south compressive stress. Nilsen and Clarke (1975) believed the Stockton arch marked the tectonic transition near the northern limit of the Paleocene right-lateral shear couple.

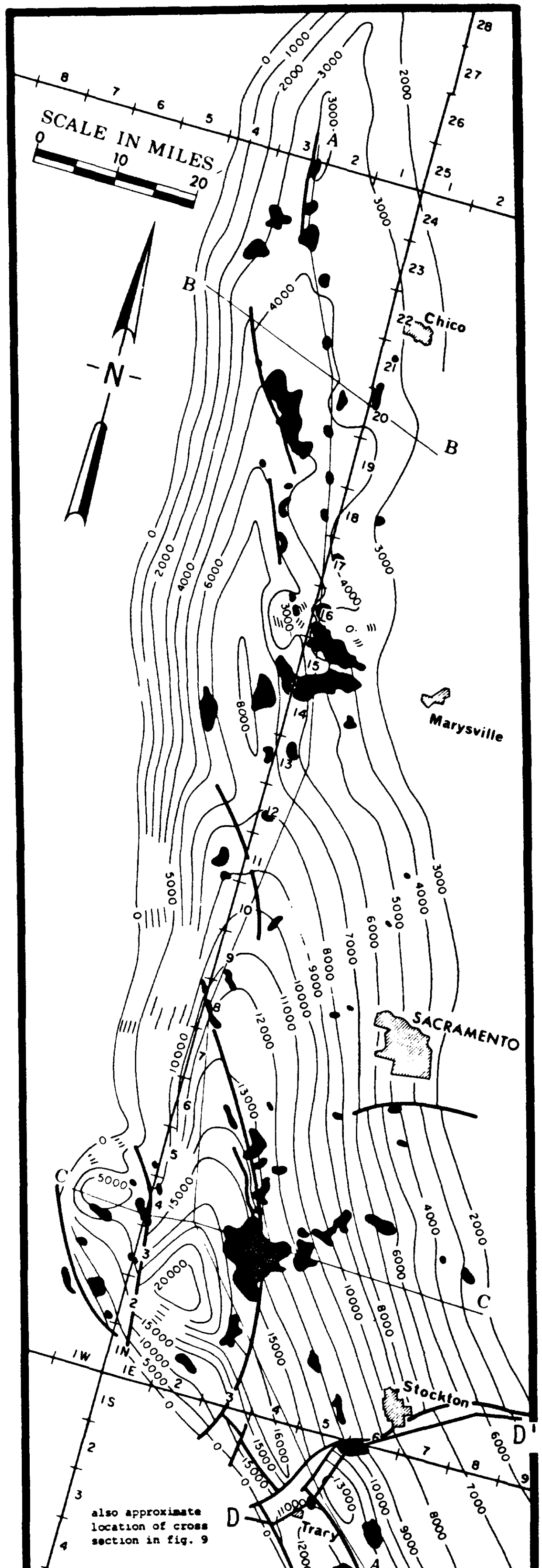

Figure 16. Isopach map of interval from base of Campanian Forbes Formation to base of nonmarine rocks in the Sacramento basin. Isopach interval is 328 m (1000 ft) (from Morrison and others, 1971). Major faults, cities and gas fields (black) also are shown along with locations of cross sections A, B, C and DD' (figs. 17, 18, and 19).

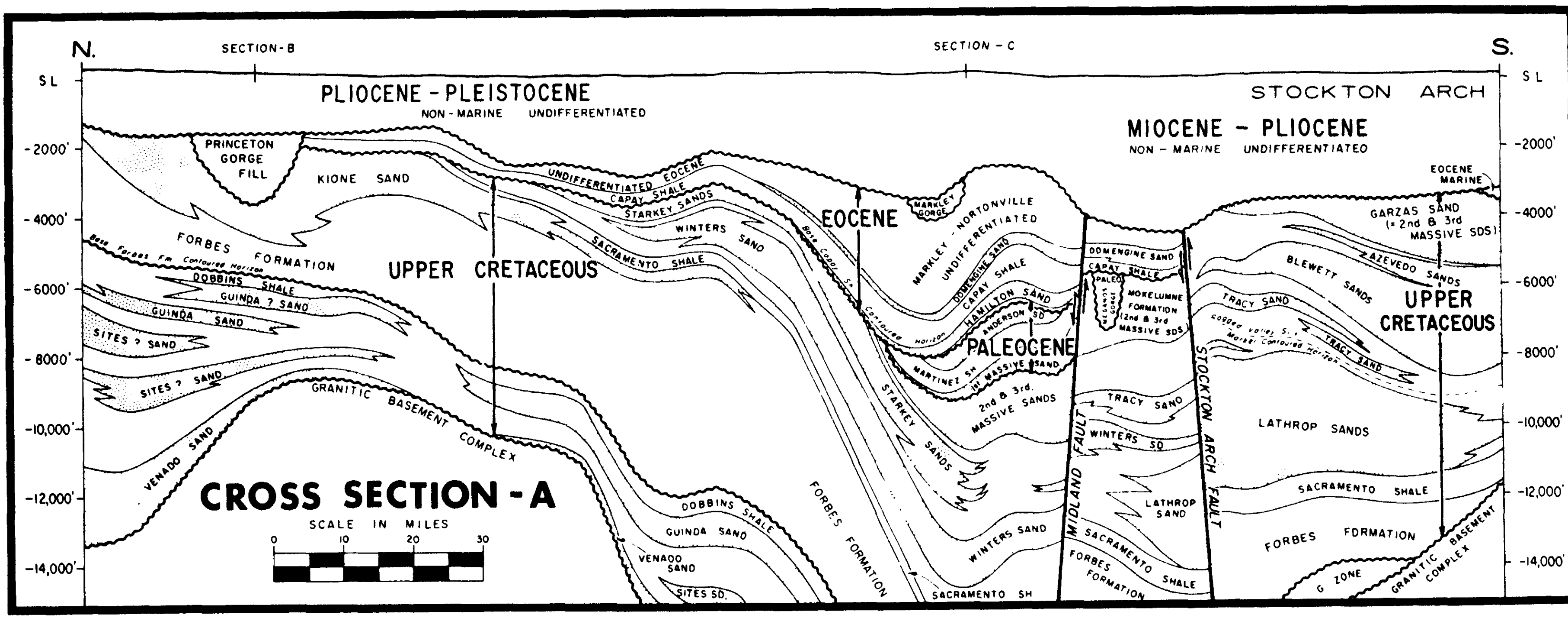

Figure 17. North-south cross section A, Sacramento basin, California (from Morrison and others, 1971). See Figure 16 for location. Present-day interpretations of stratigraphic relationships and ages may vary slightly in a few places from the interpretations of this cross section.

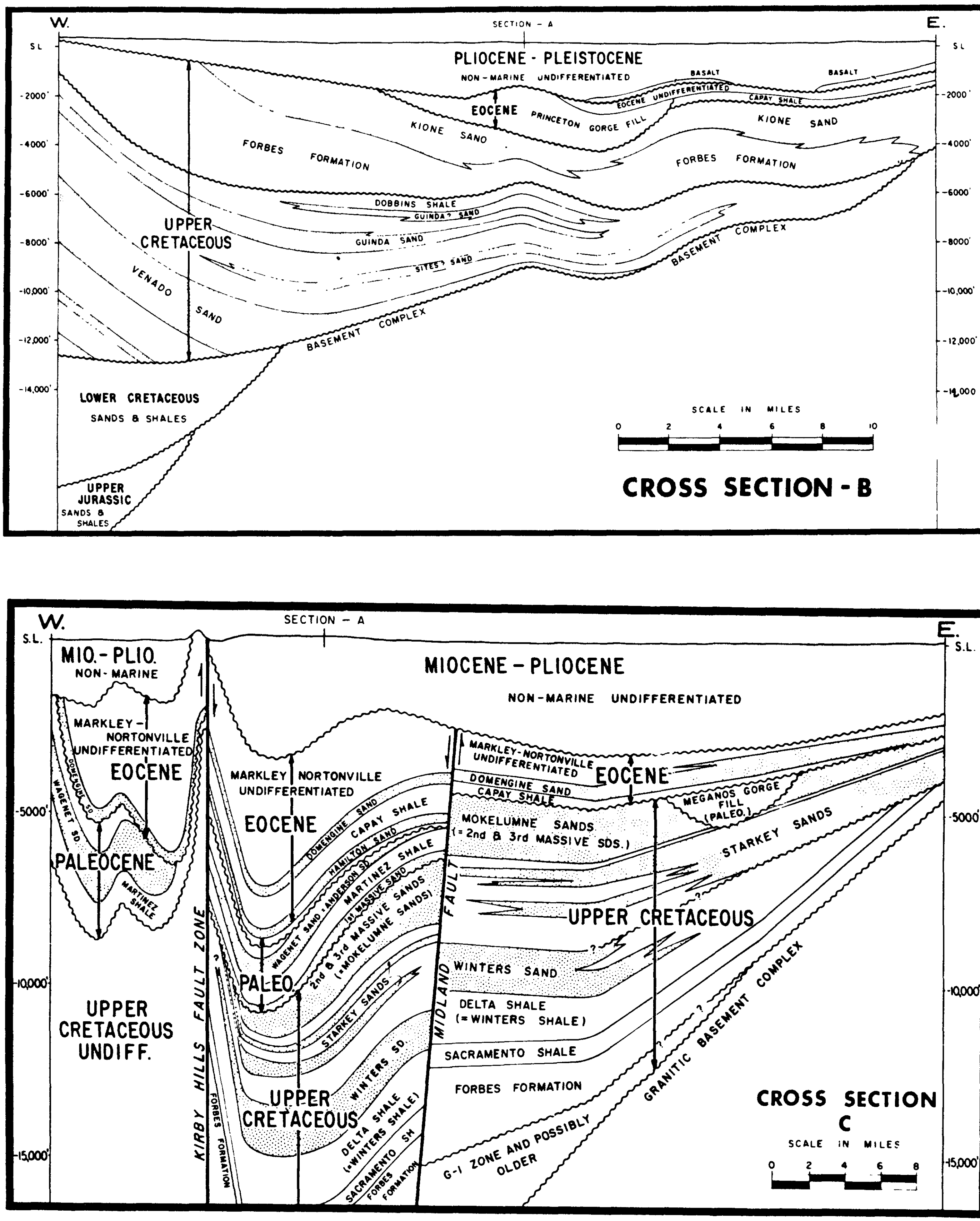

Figure 18. East-west cross sections B and C, Sacramento Basin, California (from Morrison and others 1971). See Figure 16 for location. Present-day interpretations of stratigraphic relationships and ages may vary slightly in a few places from the interpretations of these cross sections.

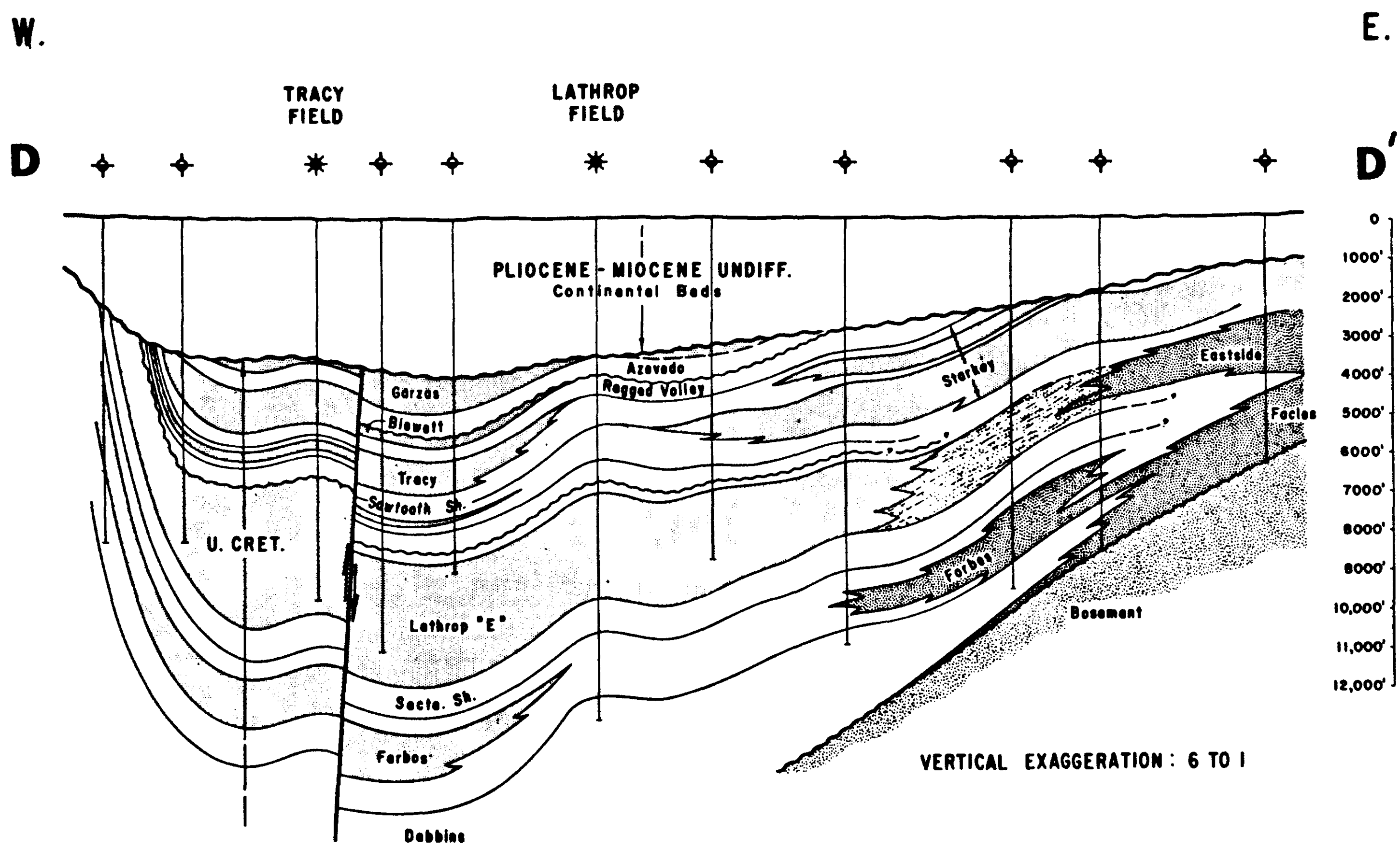

Figure 19. East-west cross section DD', southern Sacramento basin, California (From Teitsworth, 1968). See Figure 16 for location. Details of facies changes may vary slightly from more recent interpretations (e.g., Cherven, 1983a; fig. 9).

The northeast-trending subsurface Stockton fault zone (figs. 12 and 17), which bounds the Stockton arch on the north, is a south-dipping reverse fault zone that trends transversely to the regional structure. This fault zone appears to have had a complex history, but has a total down-to-the-north dip slip of up to 1,100 m (3,610 ft), most of which occurred during the Oligocene (Hoffman, 1964; Teitsworth, 1964; Bartow, 1985; Harwood and Helley, 1987).

The Thornton arch is an east-west-trending structural nose that is reflected in sandstone isopach maps from at least Maastrichtian to late Eocene (Cherven, 1983b) (fig. 12). It is crossed by a number of northwest-trending, down-to-the-west normal faults that enhance the entrapment of gas but do not cut overlying nonmarine Miocene rocks. These Miocene strata also are not affected by the arch (Silcox, 1968). The Thornton arch probably was a response to the north-south compressive stress regime like the Stockton arch and Stockton fault zone.

The Midland fault zone is a major subsurface structure that extends from south of the Rio Vista gas field about 25 km (15.5 mi) north to the Maine Prairie gas field (Arleth, 1968) (figs. 12 and 18). In the Rio Vista field, it is a steep, west-dipping to vertical fault zone that offsets Paleogene rocks down to the west (Burroughs and others, 1968; Harwood and Helley, 1987). Paleocene and Eocene units show thickening west of the fault. Almgren (1978) demonstrated about 610 m (2,000 ft) of episodic movement between early Paleocene and early Oligocene. There are no indications that early Oligocene or younger deposits are offset by the Midland fault zone (Harwood and Helley, 1987). Cherven (1983b) believed his net-sand maps showed normal faulting during Maastrichtian and also a small amount of right-lateral offset on the Midland fault zone.

The localized effects of episodic structural deformation within the Sacramento basin province beginning in Late Mesozoic has been well documented (e.g., Hackel, 1966; Safonov, 1968; Hoffman, 1972; Harwood and Helley, 1987). Faults and folds that pre-date the widespread, unconformably-overlying Eocene section were especially important to the development of gas reservoir traps (Graham, 1981) (figs. 15, 17, and 18). Periodic uplift, erosion, faulting and folding along the southwest margin of the province seem to have occurred principally in pre-early middle Eocene, pre-Pleistocene and mid-Pleistocene times (e.g., Hackel, 1966; Graham, 1981; Fischer, 1984). Folds and reactivated folds (many with reverse or thrust faults and some with topographic expression), sharp angular unconformities and homoclinal onlap-offlap depositional sequences developed locally along the southwest margin and adjacent area of the basin (Hackel, 1966; Hoffman, 1972). Deformation seems to decrease eastward in the southern part of the province (Hoffman, 1972).

Much of the Late Cenozoic deformation in the Sacramento basin appears to be due to a general east-west compressive stress regime, with local variations such as around Mount Diablo and Potrero Hills (fig. 12). Harwood and Helley (1987, p. 1) state that "In the middle Pliocene to early Pleistocene, east-west compressive deformation progressed northward through the valley so that the youngest late Cenozoic deformation is recorded in east-northeast-trending folds and faults...at the northernmost part of the valley. Much of the east-west compressive stress that affected the valley in the late Cenozoic was accommodated by east-side-up reverse movement on the steeply east-dipping, northwest-trending Willows fault and the north-trending Corning fault that splays off from the main stem of the Willows fault north of Sutter Buttes" (fig. 20). For more information about the structural deformation of the province, the reader may examine papers by Hackel (1966), Safonov (1968), and especially Hoffman (1972) and Harwood and Helley (1987).

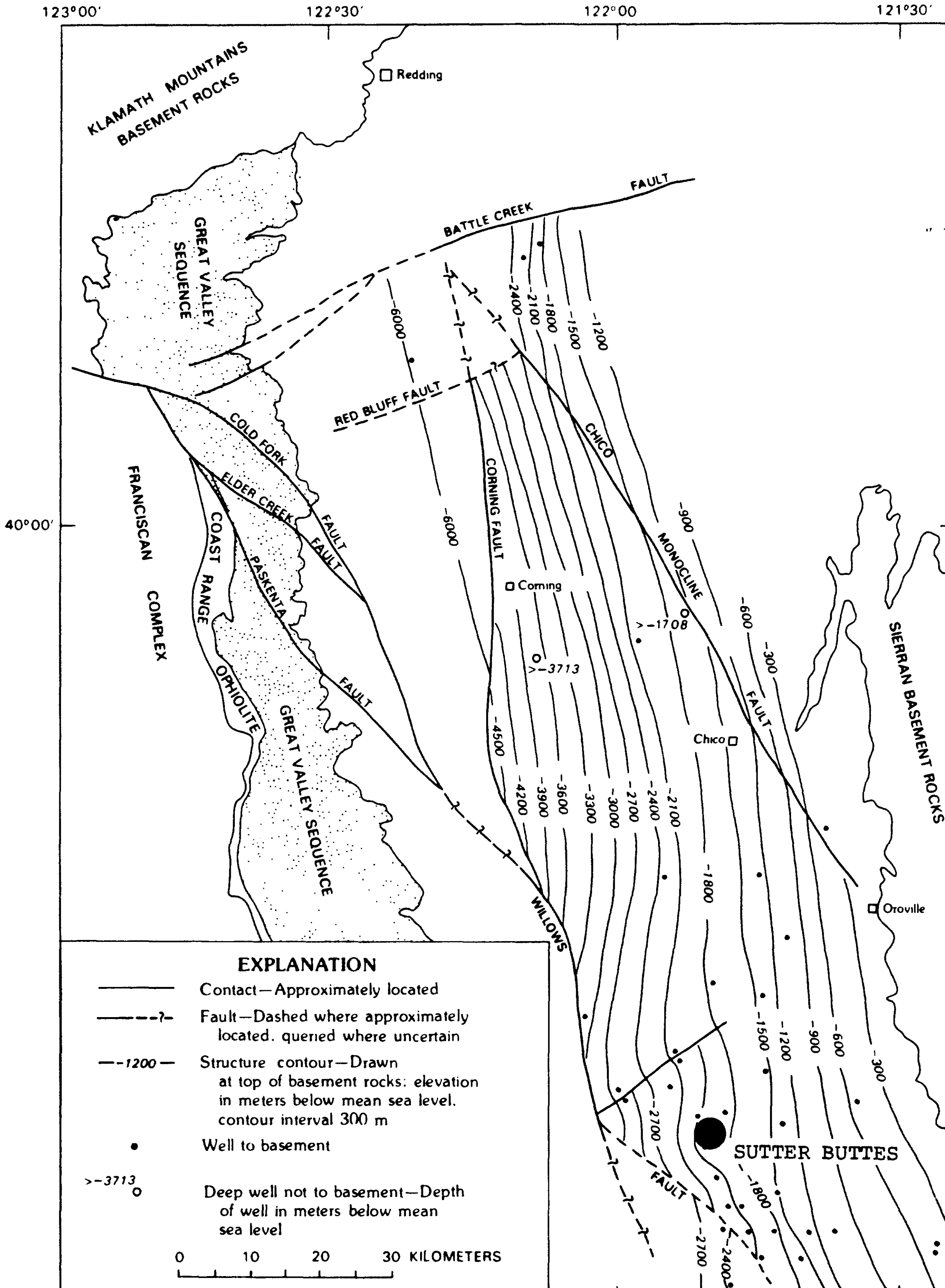

Figure 20. Map of northern Sacramento Valley showing structure contours, drawn on top of basement rocks, used to estimate amount of vertical displacement of basement across Corning fault (figure and caption from Harwood and Helley, 1987).

Heat Flow, Subsurface Temperatures and Pore-Fluid Pressures

Heat flow in the Coast Ranges, west of the Great Valley, is higher than in the Sierra Nevada to the east, a fact that Lachenbruch and Sass (1980) attributed to the rapid eastward steepening of the subduction zone across central California where heat flux from basement rocks presumably decreases eastward beneath the Great Valley. Heat flow within the Sacramento basin generally is higher along the west side than in the central and eastern basin areas, but everywhere is lower than in the Coast Ranges (Sass and others, 1971).

Published temperature data from the Sacramento basin is from mostly uncorrected or poorly corrected well log temperatures that must be viewed with caution (American Association of Petroleum Geologists, 1975; Lico and Kharaka, 1983). Lico and Kharaka (1983) concluded from uncorrected well log temperatures from more than 3,000 wells that temperature gradients range from 18 to 25 ^{o}C/km (0.99 to 1.37 ^{o}F/100 ft) in the Sacramento basin but are locally higher in the Delta depocenter, between 25 and 35 ^{o}C/km (1.37 and 1.92 ^{o}F/100 ft), due to the lower thermal conductivity of the Upper Cretaceous rocks buried beneath the Tertiary section and decreased convective fluid flow there. They offer no documentation of these latter assertions.

Carefully measured temperature gradients in water wells, though few in number, range from 3.6 to 32 ^{o}C/km (0.20 to 1.75 ^{o}F/100 ft) and suggest that temperature gradients are higher along the southwest margin of the basin (Wang and Munroe, 1982) (fig. 21).

Little is published about the thermal history of the Sacramento basin except for Dumitru (1988) who determined maximum burial temperatures from apatite fission track analysis and used backstripping to reconstruct burial histories of late Mesozoic forearc basin sediments. He argued that thermal gradients were continuously subnormal in the forearc basin from the beginning of Franciscan subduction in Late Jurassic until termination of subduction in late Cenozoic, an important consideration for the time of generation and source depth of natural gas.

High pore-fluid pressures, markedly greater than hydrostatic, have long been recognized in different parts of the Sacramento basin. Weagant (1972) gave an excellent published example of abnormally high pore-fluid pressures and discussed their implications for gas accumulations in the Grimes gas field. Fluid pressure data from multiple drill-stem tests in many wells showed that (1) formation pressures increase markedly above hydrostatic starting at about 1,674 m (5,500 ft); (2) formation pressures differ considerably among the various fault blocks of the Grimes field for reservoirs at the same depth, generally decreasing from fault block to fault block in an easterly direction; and (3) sandstones in fault blocks with lowest pressure contain more and larger gas accumulations, in accordance with hydrodynamic theory. Dependence of gas accumulations on present-day fluid pressures suggested to Weagant that late-stage migration or late-stage modification of pre-existing accumulations occurred. He states that the present fluid pressures probably originated with the intrusions and uplift associated with the Sutter Buttes volcanic center formed about 2.4 to 1.4 Ma (Williams and Curtis, 1977).

Berry (1973) systematically studied pore-fluid pressures in Great Valley, derived mostly from extrapolation of shut-in pressure curves, and concluded that high pore-fluid potentials occur in a regional band along the western side of the valley. These high fluid pressures generally increase westward and with increasing depth, and approach the surface where overlying low-transmissibility rocks do, such as at the Lost Hills oil field in the San Joaquin basin (Berry, 1973, 1980). Berry (1973) believed the high pore-fluid potentials were derived from the combined effects of gravitational compaction and local and regional compression of the very thick Great Valley sequence which expelled pore-waters, to the extent that transmissibility permitted, into the overlying section.

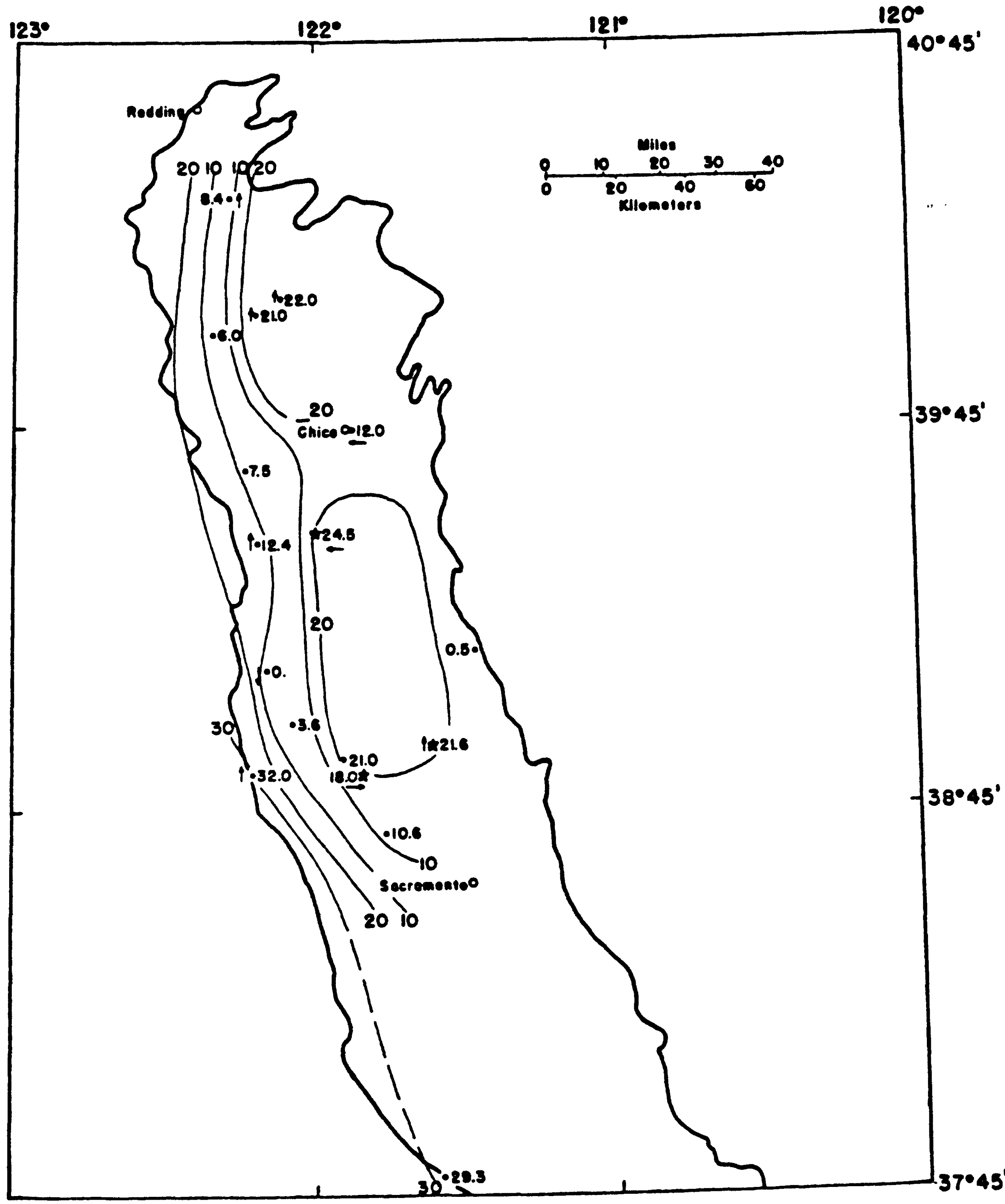

Figure 21. Temperature gradient map of the northern portion of the Great Valley, California, based on measurements in water wells (Wang and Munroe, 1982). Contour interval is 10 $^{o}C/km$.

Lico and Kharaka (1983) reported pore-fluid pressure zones in the eastern, western, and northern parts of the Sacramento basin that have hydraulic pressure gradients greater than .206 kPa/m (>0.433 psi/ft) at depths less than 1,200 m (<3,937 ft), based on examination of sonic and conductivity logs (fig. 22). These zones occur at progressively greater depths toward the center of the basin, where they may exceed 3,000 m (9,842 ft). In the Delta depocenter, hydraulic pressure gradients greater than .206 kPa/m (>0.433 psi/ft) may occur as shallow as 1,500 m (4,921 ft) in Tertiary rocks, according to Lico and Kharaka (1983). Rapid subsidence and compaction with associated thermal expansion of pore waters due to increased temperatures (Barker, 1972) is suggested as the cause of deep, abnormally high pore-fluid pressures in the Delta depocenter (Lico and Kharaka, 1983). Also, "fossil" pore-fluid pressures caused by uplift and erosion are believed to be the cause of abnormally high fluid pressures in some parts of the basin (Lico and Kharaka, 1983).

Petroleum Source Rocks

With minor exceptions, the Sacramento basin is a dry gas province. Mesozoic marine rocks generally contain type III kerogen and less than 1% total organic carbon (Trask and Hammar, 1934; Zieglar and Spotts, 1978; Larue and Underwood, 1986; Graham, 1987) (fig. 23A). Oil-prone source rocks of Eocene age are exposed in the northeastern Diablo Range south and west of the Brentwood oil field and occur in the subsurface in the Delta depocenter, but little is published about their distribution, volume or characteristics (Jefferis, 1984). Possibly, these units are the source rocks for the small amounts of oil and condensate that are found mostly in the central and western delta region (fig. 24).

Hydrocarbon generation depends on the time-temperature history of the source rocks. The concepts of temperature windows, within which oil or gas is generated, can be used to model this process in a rudimentary way (e.g., Waples, 1980). This approach was used by Zieglar and Spotts (1978) to construct a burial history/hydrocarbon maturation diagram (so-called Lopatin diagram) for the Delta depocenter of the Sacramento basin (fig. 23B). This Lopatin diagram was con-structed by using present-day sedimentary rock thicknesses (Graham, 1987), a geothermal gradient of 2.72 ^{o}C/100 m (1.49 ^{o}F/100 ft), assumed constant over time, and sedimentation rates assumed to be fairly uniform over time within each age unit (Zieglar and Spotts, 1978). Based on these assumptions, gas generation from Cretaceous source rocks in the Delta depocenter commenced about 70 to 80 Ma, according to Zieglar and Spotts (1978).

Graham and Williams (1985) believed the assumed geothermal gradient used by Zieglar and Spotts (1978) is too high for the Mesozoic forearc basin and report that, based on analysis of outcrop samples, much of the Mesozoic section resides in the "oil window" or is even immature; they concluded that the gas origin is not necessarily thermogenic in the conventional sense, but must be related to gas-proneness of the kerogen.

The origin of the natural gases of the Sacramento basin has been an intriguing question because of the (1) systematic increase in the nitrogen content of the gases eastward from the center of the basin and downward stratigraphically, and (2) lack of source rocks in the gas generating thermnal window beneath all parts of the basin (Morrison and others, 1971; Graham and Williams, 1985). Berry (1965) prophetically suggested that the nitrogen in the gases originated from low-grade metamorphism of sedimentary rocks that contained organic matter and that the Franciscan Formation was the likely source.

Berry (1965) waited about 20 years for published substantiation of his ideas by Poreda and others (1986), Jenden and others (1988) and Jenden and Kaplan (1989). These authors concluded from a thorough chemical and stable isotope analysis of gas samples from 94 producing wells in the Sacramento basin that gases were of four principal types: (1) gas of relatively high heat value

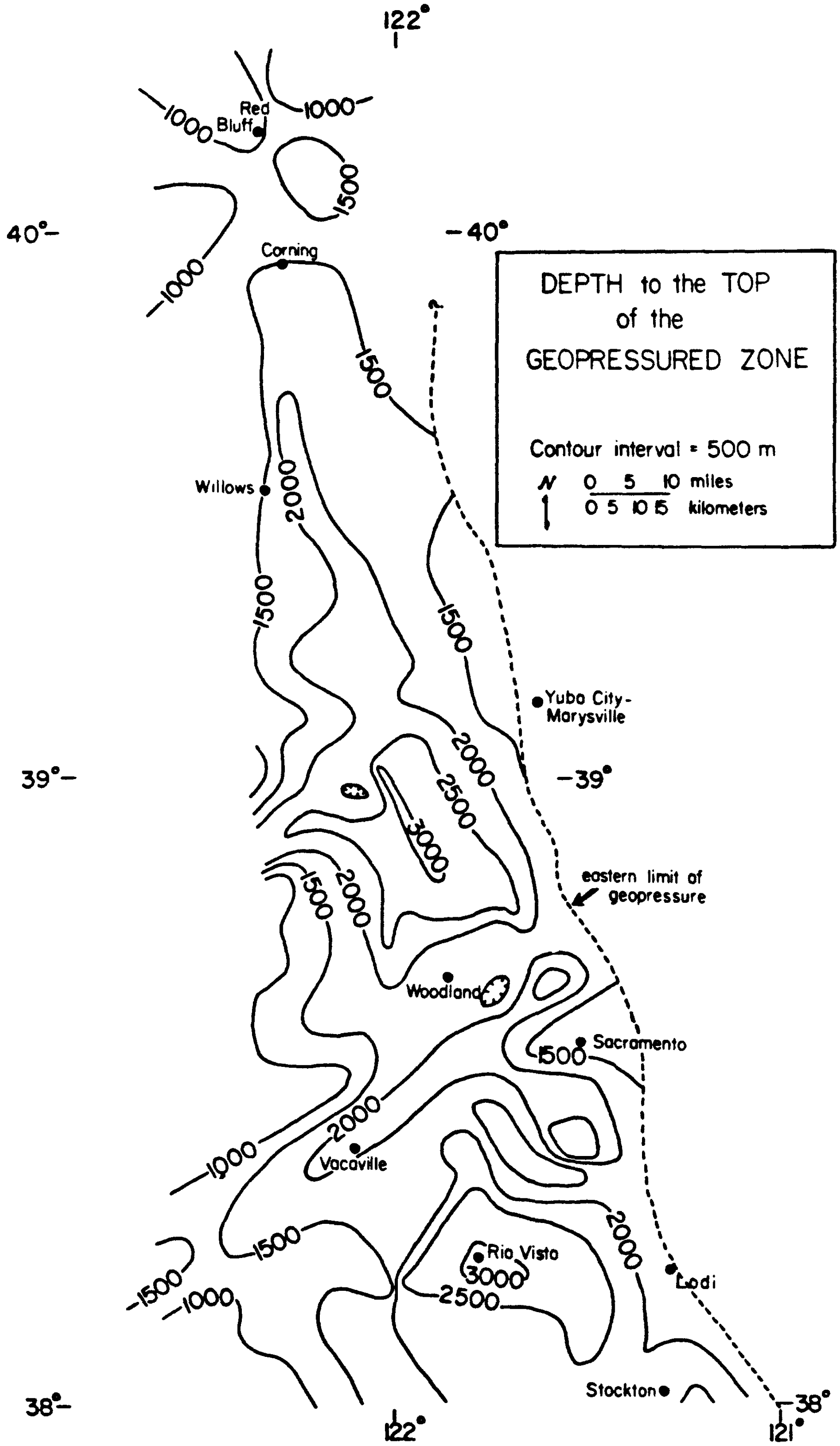

Figure 22. Contour map of depth to top of abnormally high pore-fluid pressure zone in the Sacramento basin (Lico and Kharaka, 1983). Contour interval is 500 m. Dotted line represents eastern limit of geopressured rocks.

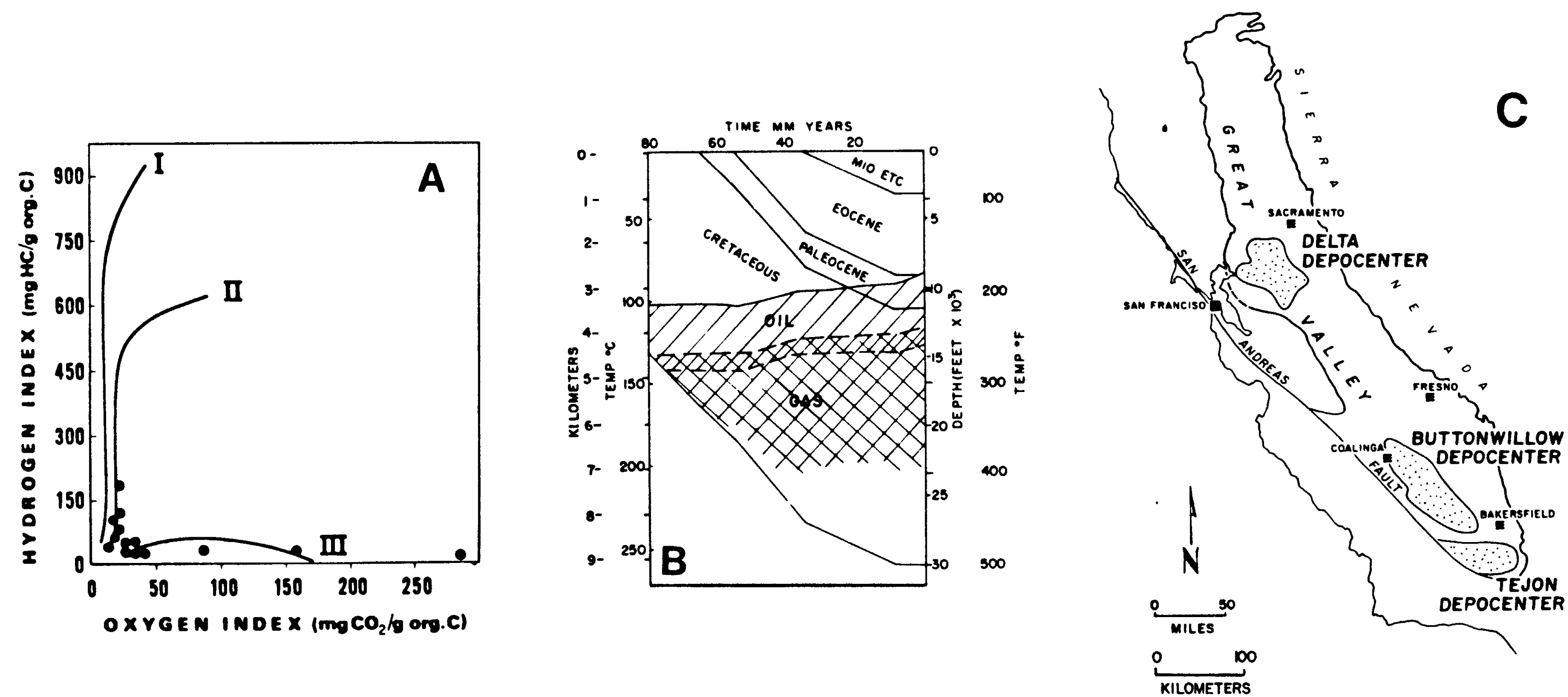

Figure 23. (A) Modified Van Krevelen diagram that gives the hydrogen versus oxygen richness of source rocks from Jurassic through Campanian exposures west of Sacramento (Graham, 1987). (B) Burial-history/petroleum maturation diagram for Delta depocenter of the Sacramento basin (Zieglar and Spotts, 1978). (C) Map of Tertiary depocenters, including the delta depocenter, of the Great Valley, California (Zieglar and Spotts, 1978).

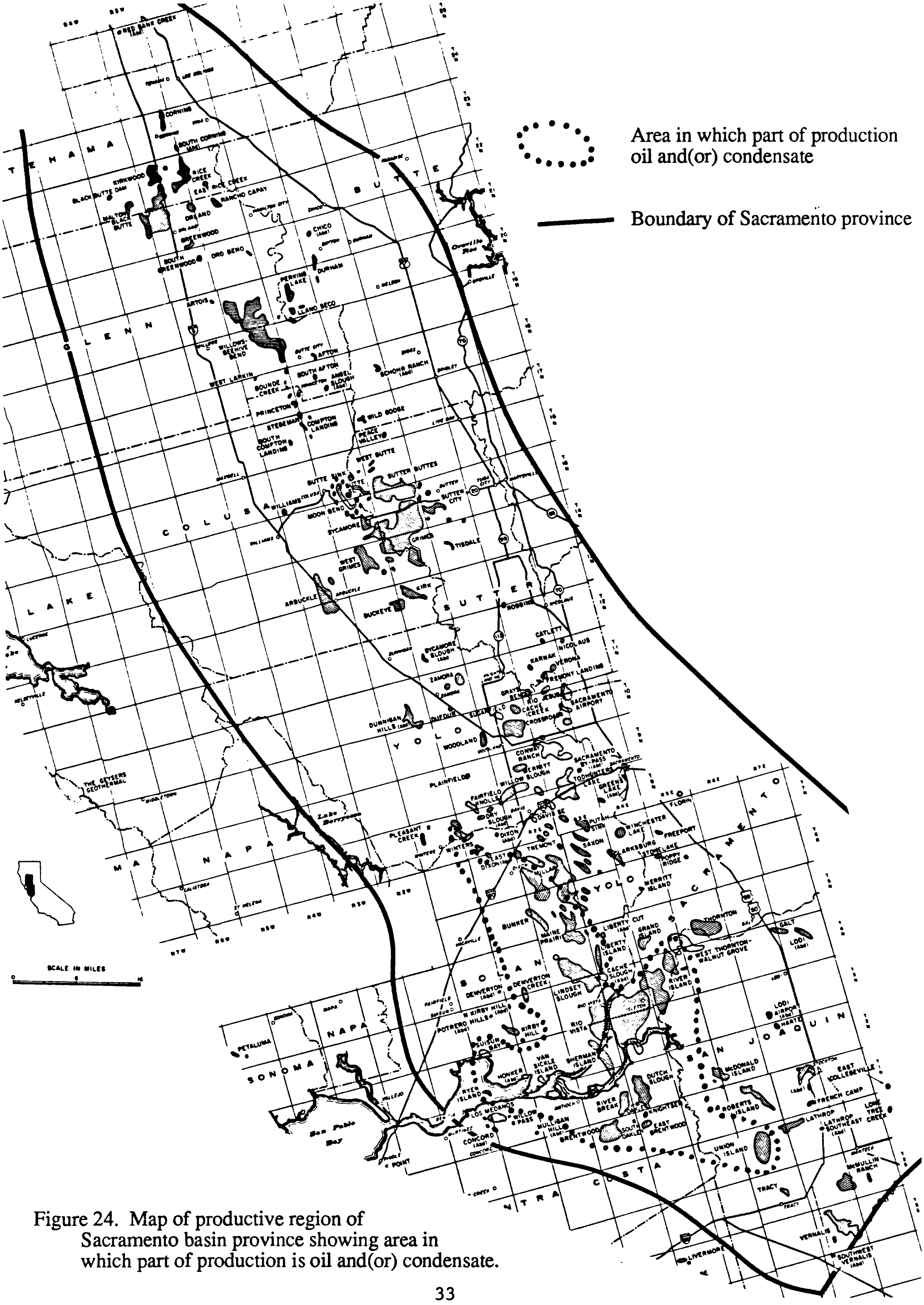

Figure 24. Map of productive region of Sacramento basin province showing area in which part of production is oil and(or) condensate.

generated from source rocks in the oil and condensate window in the western Delta depocenter, (2) indigenous diagenetic gas (mostly microbial methane), (3) dry thermogenic gas from post-mature source rocks in the basin deep, and (4) nitrogen-rich gas of relatively low heat value thought to originate in metasedimentary rocks (subducted Franciscan complex) deep within the basement. Jenden and Kaplan (1989) suggested that gases in the northern and southeastern parts of Sacramento basin have complex origins that involved the migration and mixing of the latter three types of gas. Methane derived from microbial and thermogenic alteration, however, were reported to be dominant in the basin.

Diagenesis of Petroleum Reservoir Rocks

Sandstones of the Sacramento basin are thought to be derived mostly from the Cordilleran magmatic arc system to the east and northeast (e.g., Dickinson and Rich, 1972). These sands generally are mineralogically immature and may contain significant amounts of feldspar, mica, igneous and metamorphic rock fragments, and(or) argillaceous matrix, making them more susceptible to diagenetic alteration than, for example, the more mineralogically mature sandstones of the Gulf Coast. Diagenesis of mineralogically immature sandstones in California Cenozoic basins has received increased attention in recent years, presumably because exploration for subtle and deeper reservoirs, as well as improved recovery efficiency from existing reservoirs, requires better understanding and prediction of reservoir porosity, permeability, and timing of hydrocarbon migration. The long-standing tradition of cutting and archiving conventional cores has been invaluable to these more recent investigations. See Beyer and Bartow (1988) for a description of diagenetic studies of immature sandstones in the San Joaquin basin that has some applicability to the Sacramento basin, where far fewer studies have been published.

Dickinson and others (1969) found widespread albitization of plagioclase and chloritization of biotite in latest Tithonian to earliest Maastrichtian, noncalcareous sandstones of the Great Valley sequence exposed on the west side of the Sacramento Valley. They concluded that these alterations (1) are less common in calcareous sandstone, (2) appear to begin below an inferred burial depth of about 2,286 m (7,500 ft) and to intensify systematically with greater age and burial depth in the Upper Cretaceous sequence, and (3) are uniformly great in Lower Cretaceous strata that probably were buried to depths of 6,096 m (20,000 ft) to 9,144 m (30,000 ft). Laumontite is characteristic of thoroughly altered Lower Cretaceous rocks exposed along the west side of the Sacramento Valley. This sequence of rocks appears to be ideal for various types of diagenetic studies--studies that might reveal the thermal history and chemical evolution of the sequence.

Within the Sacramento basin, Suchecki (1980) described coatings on framework grains of chlorite, pore-filling chlorite or calcite, and finally late replacement of framework grains by chlorite in sandstones of the Great Valley sequence (Tithonian to Hauterivian stages). Mertz (1988) examined sandstones from the Upper Cretaceous Forbes Formation and found sequential diagenetic events that included (1) development of clay rims on framework grains; (2) early dissolution of unstable framework components and selective replacement by illitic clays and(or) calcite; (3) widespread cementation by K-feldspar, quartz, calcite, mixed-layered illite-smectite; (4) albitization of K-feldspar; (5) extensive dissolution with local development of secondary porosity; and (6) the formation of porosity-occluding kaolinite, chlorite, pyrite, calcite and zeolites. Development of secondary porosity was observed to be highly localized within given reservoir units.

Smith and Berry (1988) examined shale cuttings from the Forbes Formation in the Grimes gas field and found that the smectite-to-illite conversion begins at about 2,134 m (7,000 ft) at a temperature of about 80 ^{o}C (176 ^{o}F). This smectite-to-illite conversion yields silica and eventually water that, respectively, appear to correlate with decreases in permeability and the occurrence of zones of overpressuring in the Forbes.

Porosity of Petroleum Reservoir Rocks

Porosity and permeability of sandstones are governed by compactional and diagenetic processes. These processes are controlled by such factors as the original detrital mineralogy, texture, and organic content of the sandstone, its depositional environment and rate of burial, and post-burial histories of temperature, pore-fluid chemistry, pore-fluid pressure, and confining stresses (McCulloh, 1967).

Unfortunately, little definitive information has been published on the systematics of sandstone porosity and permeability in the Sacramento basin. Zieglar and Spotts (1978) suggested a porosity loss of about 4.2 porosity percent per kilometer (1.4 porosity percent per 1,000 feet) of burial from an initial value of 37% at the surface for sandstone reservoirs in the Sacramento basin and eastside of the San Joaquin basin (fig. 25). This conclusion, based on estimated average reservoir porosities from the California Division of Oil and Gas, may be valid for the younger, late Tertiary rocks of the eastside of the San Joaquin basin but probably cannot be applied to the older rocks of the Sacramento basin. Graham (1981) stated that the data of Figure 25 probably does not apply to the lithofeldspathic sandstones of the older Mesozoic sequence, which tend to deform and develop "pore-clogging pseudomatrix" under great burial loads.

The effects on reservoir porosity and permeability of widespread abnormally high pore-fluid pressures in the Sacramento basin is poorly understood and documented. Also, porosity- and permeability-altering diagenetic processes are not well understood in Sacramento basin reservoirs, which generally are much older than those in the San Joaquin basin. A definitive study of reservoir porosity and permeability in the Sacramento basin remains to be done, in the author's opinion.

Reservoir Trap Types

The surprising variety of trap types in the Sacramento basin has been described by many workers but the description paraphrased here, from Graham (1981), is perhaps the most complete:

(1) Stratigraphic-structural traps involving sand pinchouts updip and across structural noses are common, especially in Cretaceous deltaic and basinal facies in the north-central part of the Sacramento basin.

(2) Faulted folds are common traps throughout the basin.

(3) Simple, unfaulted anticlines occur but are less common.

(4) Gorge truncation traps are a special type of stratigraphic trap in which impermeable gorge fill forms the reservoir seal--often in conjunction with faulting that provides lateral closure (e.g., Hunter and others, 1984). These types of traps are important in the areas of the Paleocene gorges.

(5) Gorge fill traps are a special type of stratigraphic trap in which lenticular channel sands occur within the otherwise impermeable gorge fill. These are less common than gorge truncation traps.

(6) Unconformity traps are found where overlying transgressive shale has sealed underlying sands.

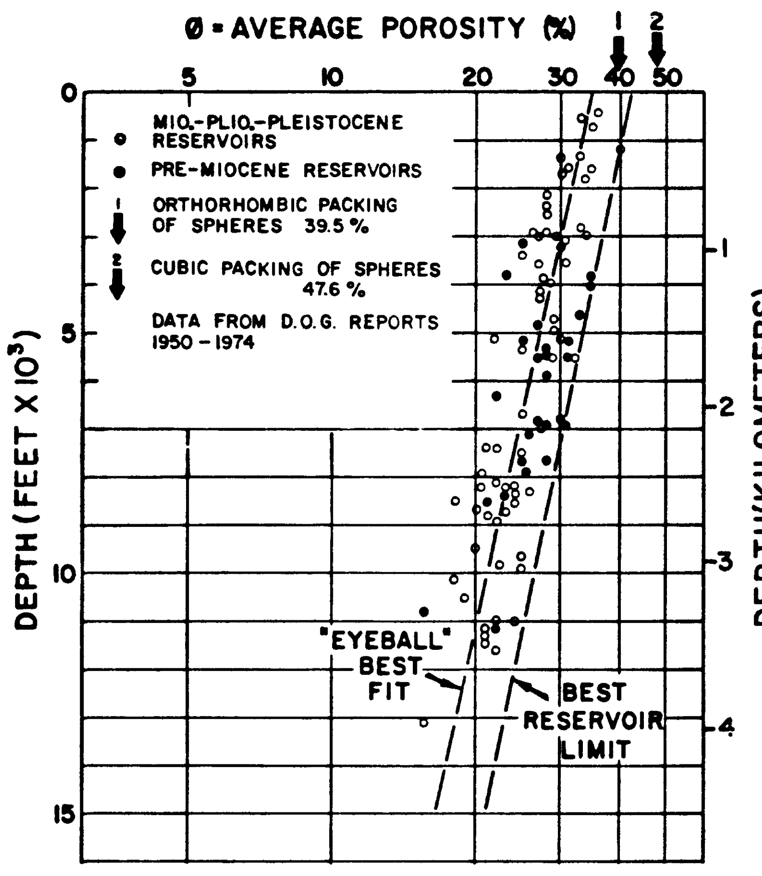

Figure 25. Porosity-depth plot for sandstone reservoirs from Sacramento basin and eastside of San Joaquin basin (Zieglar and Spotts, 1978).

(7) Structural traps are associated with volcanic intrusive plugs at Sutter Buttes and probably beneath the Wild Goose gas field. Intrusions caused upwarping and shattering of the sedimentary section. The resultant traps are analogous to those flanking salt piercement structures.

Added to this list is the anticlinal type formed near the edges of submarine canyon fill by compaction of that fill (see Edmondson, 1972).

PETROLEUM PLAYS

The play concept in the analysis of petroleum resources is defined as a group of hydrocarbon prospects and/or discovered accumulations that have common geological characteristics such as source rock, trapping mechanism, structural history or depositional pattern (Procter and others, 1982). Within a basin, play definition is a subjective process and different workers may define different numbers of plays based on different criteria. For the 1987 petroleum assessment of the Sacramento province, four plays were defined primarily on the basis of stratigraphic interval. Because the USGS resource assessment by play analysis utilized statistical data of discovered accumulations within the play, the need to logically group the large number of discovered gas reservoirs in the basin also influenced play definition. The four plays are described below by proceeding from oldest to youngest rock units. For each of the four plays, averages and ranges of reservoir depth, net sand thickness, porosity and gas heating value are given in Table 2.

PLAY I: Kione-Forbes-Pre-Forbes and Southern Equivalents

This play includes Late Jurassic (Tithonian) through middle Late Cretaceous (mid-Campanian) marine clastic rocks of the Great Valley sequence that, proceeding from oldest to youngest, belong to the Stoney Creek, Lodoga, Boxer, Venado, Yolo, Sites, Funks, Guinda and Forbes formations (Lawton, 1956) or their equivalents. This play encompasses virtually all of the Sacramento basin province because parts of the Great Valley sequence underlie the entire region (fig. 26).

All significant, discovered gas reservoirs of this play are in the Kione deltaic facies (fig. 26) and other more distal facies of the Forbes formation in the northern basin area north of T. 12 N (fig. 26). In this northern area, minor gas reservoirs also have been found in the underlying sands of the Dobbins shale and Guinda Formation, generally along a trend that extends from the Nicolaus field north-northwestward to the Willows-Beehive Bend field (fig. 26). South of T. 12 N uneconomic to minor Forbes gas accumulations have been discovered on the eastern shelf (Robbins, Clarksburg, Poppy Ridge, and East Collegeville fields), in the Dunnigan Hills field, and possibly in the western delta area (Kirby Hill and Los Medanos fields) (fig. 26). Elsewhere in the deeper parts of the basin, south of about T. 7 N, the top of the Forbes occurs at depths that range from about 3,050 to 4,265 m (10,000 to 14,000 ft) and sparse testing by drilling has not found economic gas accumulations. Hoffman (1972) stated that limited drilling into the deep Forbes south of the Stockton fault zone found sands to be scarce and tight.

This play is capped by the Sacramento or equivalent Pleasant Valley shale throughout most of the basin except in the north, where the Kione deltaic facies of the Forbes is unconformably overlain by the Eocene Capay shale, Princeton gorge fill, or younger nonmarine rocks (fig. 17).

Gases in the northern part of the basin may be largely thermogenic, probably derived from deeply buried shale and mudstone along the western margin and, possibly, from the now-missing western part of the forearc basin (Jenden and Kaplan, 1989). Gases with higher nitrogen content on the eastern flank (e.g., Robbins, Nicolaus, East Collegeville fields) may be derived largely or in part from metasedimentary rocks located deep beneath the basement (Berry, 1965; Jenden and

Table 2. Reservoir depth, thickness, porosity and gas BTU by petroleum play for gas fields of Sacramento basin. Average values and ranges (in parentheses) are computed from California Division of Oil and Gas (1982).

	Reservoir Depth (m & ft)	Reservoir Thickness (m & ft)	Reservoir Porosity(%)	Gas Heating Value (BTU)/ft^3
PLAY I	550 m 1,805 ft (305 - 975 m) (1,000 - 3,200 ft)	9 m 30 ft (2 - 21 m) (5 - 70 ft)	29 % (15 - 33 %)	870 (760 - 1,020)
PLAY II	1,212 m 3,975 ft (305 - 2,384 m) (1,000 - 7,822 ft)	14 m 46 ft (1 - 96 m) (3 - 315 ft)	26 % (15 - 34 %)	997 (711 - 1,126)
PLAY III	1,589 m 5,213 ft (439 - 3,118 m) (1,440 - 10,228 ft)	11 m 36 ft (1 - 168 m) (2 - 550 ft)	27 % (14 - 35 %)	918 (700 - 1,083)
PLAY IV	1,450 m 4,757 ft (427 - 3,383 m) (1,400 - 11,100 ft)	11m 36 ft (1 - 81 m) (1 - 265 ft)	24 % (15 - 33 %)	923 (684 - 1,035)

Figure 26.
Map showing Sacramento province boundary, PLAY II boundary, gas and oil fields, and some geographic features and roads (California Division of Oil and Gas, 1982, updated through 1988).

others, 1988). Graham (1981) speculated that oil seeps in rocks of the Great Valley sequence, near the structural contact with the Franciscan assemblages along the western margin of the province, may come from (1) oil-prone basal units on the never-deeply-buried oceanward side of the forearc basin, or (2) from early forearc slope sediments possibly deposited in an early anoxic, restricted circulation phase of forearc basin development.

Future prospective areas of this play include (1) further Kione-Forbes-Guinda discoveries in the northern part of the basin, and (2) problematical to extremely speculative Forbes or pre-Forbes reservoirs at great depths in the southern part of the basin, pre-Guinda reservoirs in the northern part of the basin, and oil reservoirs along the western margin.

PLAY II: Starkey-Winters-Mokelumne River and Southern Equivalents

This play contains Late Cretaceous (late Campanian through Maastrichtian) marine clastic rocks south of Sutter Buttes and, in the extreme south and western delta area, some conformably overlying earliest Paleocene marine clastic rocks. This sedimentary sequence generally represents a southward and westward progradational depositional system that, with interspersed transgressive phases, eventually led to the filing of the basin (e.g., Drummond and others, 1976; Cherven, 1983a). The area of this play is shown in Figure 26. Most gas fields south of T. 13 N contain reservoirs in this play, although these reservoirs are not always the dominant ones of the fields.

The play includes basinal sands of the Winters Formation and shelf (largely deltaic) sands of the Starkey (including such local names as Petersen and H & T) and Mokelumne River (including such local names as Bunker, Midland, McDonald Island, 2nd Massive, 3rd Massive) formations north of the Stockton fault zone. South of the Stockton fault zone, widely used nomenclature refers generally stratigraphically and age-equivalent basinal and slope sands to the upper Panoche Formation (including such local names as Lathrop, Benetti, Tracy, Ragged Valley and Blewett) and Moreno Formation (including such local names as Azevedo and Garzas) (see Cherven, 1983a, fig. 3).

Rocks of this play are bounded below by the transgressive, mid-Campanian Sacramento shale which forms the uppermost part of PLAY I (fig. 17). The top boundary of this play generally is an unconformity that is overlain by the (1) Eocene marine Capay Formation in the north, (2) Paleocene marine Martinez Formation or Paleogene submarine canyon fill in the Delta depocenter, and (3) nonmarine Neogene rocks south of the Stockton fault zone (figs. 17, 18, and 19). The Paleocene Martinez Formation conformably overlies the sequence of this play locally in the western Delta depocenter (Nilsen and Clarke, 1975).

Gas reservoirs of this play probably were sourced mainly by thermogenic gas from the deepest parts of the basin, although Jenden and Kaplan (1989) believe other sources and mixing contributed in some areas and fields (Jenden, 1989, personal communication; also see Petroleum Source Rock section).

Future exploration of this play is well summarized by Cherven (1983a, p. 772) who described the occurrence of discovered reservoirs as follows:

> "Gas is produced from deltaic and submarine fan deposits. Delta-front sand beds form very small reservoirs where growth faults provide subtle structural traps. Distributary-channel sand beds are highly productive, owing mainly to stratigraphic pinchouts but locally perhaps to structural traps. Submarine fan traps have so far been located mainly in midfan deposits, either in the structurally high suprafan mounds or along lateral fan margins near the base of the slope where fan deposits onlap and pinch out against slope shale. Exploration in lower and upper fan deposits has barely begun."

While this play is in a mature exploration stage, new discoveries of mostly smaller reservoirs and possibly several larger reservoirs can be expected to continue for some time within the boundary of the play.

PLAY III: Paleocene-Eocene

This play includes marine sands of the (1) mostly Paleocene Martinez Formation (McCormick, 1st Massive, Anderson, Wagenet sands of local usage in the Delta depocenter), (2) Early Eocene Capay Formation (Hamilton sand of local usage in the Delta depocenter), (3) late Early Eocene Domengine (=Ione) Formation, and (4) Middle Eocene Nortonville and Markley formations. Marine sands in the early Eocene fill of the Princeton submarine canyon and undifferentiated Eocene Capay Formation, both in the northern part of the basin, also are included in this play along with sands in the early Eocene fill in the Meganos submarine canyon in the southern part of the basin (figs. 17 and 18). The area of this play is shown in Figure 27.

The mostly shallow marine sands of this play were deposited during three transgressive-regressive marine depositional cycles and one younger partial cycle between early Paleocene and early Oligocene time (Almgren, 1984; Cherven, 1983b). Emergence, erosion and cutting of Paleogene submarine canyons, interrupted widespread deposition of these shelf sands and their intervening deep-water shales approximately at (1) the beginning of Paleocene time, (2) the Paleocene-Eocene boundary, and (3) the Eocene-Oligocene boundary (figs. 14, 17, and 18).

Rocks of this play are bounded below by the widespread unconformity at the top of the Cretaceous section (see PLAY II description). The top of the play is bounded by post-Eocene unconformities overlain by Miocene and younger nonmarine sediments, except in the Markley submarine valley where mostly Oligocene marine sediments overlie an early Oligocene unconformity (Almgren, 1984).

Unlike the marine sands of PLAYS I and II, the reservoir sands of this play mostly are extensive shelf sands whose present distribution and limits are locally controlled by (1) several periods of faulting and folding, (2) erosional unconformities related to marine regression and emergence and the cutting and filling of submarine valleys, and (3) general westward tilt of the basin and probable uplift along the southwest margin (e.g., Hackel, 1966; Graham, 1981; Cherven, 1983b). Most reservoir traps have a structural element or involve updip erosional truncation. The variety of stratigraphic intervals and trap types involved is large, and the reader is invited to examine Almgren and Hacker (1984), Graham (1981), Cherven (1983b), and California Division of Oil and Gas (1982).

Gases trapped in reservoirs of this play probably are thermogenic and were derived from source rocks in the basin deep and shallower source rocks, some of which may be within the play sequence, that are presently within the "oil window" in the Delta depocenter (Graham, 1981; Jenden and Kaplan, 1989). In the northern basin area, the origin of the gas is as suggested for PLAY I in that area.

PLAY III rocks are well explored in the Sacramento basin. However, because of the considerable complexity of the distribution of the many gas discoveries in this play, more discoveries are certain, but their size in relation to past discoveries will continue to diminish.

PLAY IV: Post-Eocene

This play includes all post-Eocene rocks but, based on discovered gas occurrences, consists principally of the nonmarine "upper Princeton Valley fill" (Redwine, 1984) in the northern area, marine sands in the Oligocene fill of the Markely submarine valley, and nonmarine rocks of the Miocene Valley Springs Formation and Mio-Pliocene Mehrten Formation in the southernmost part of the basin.

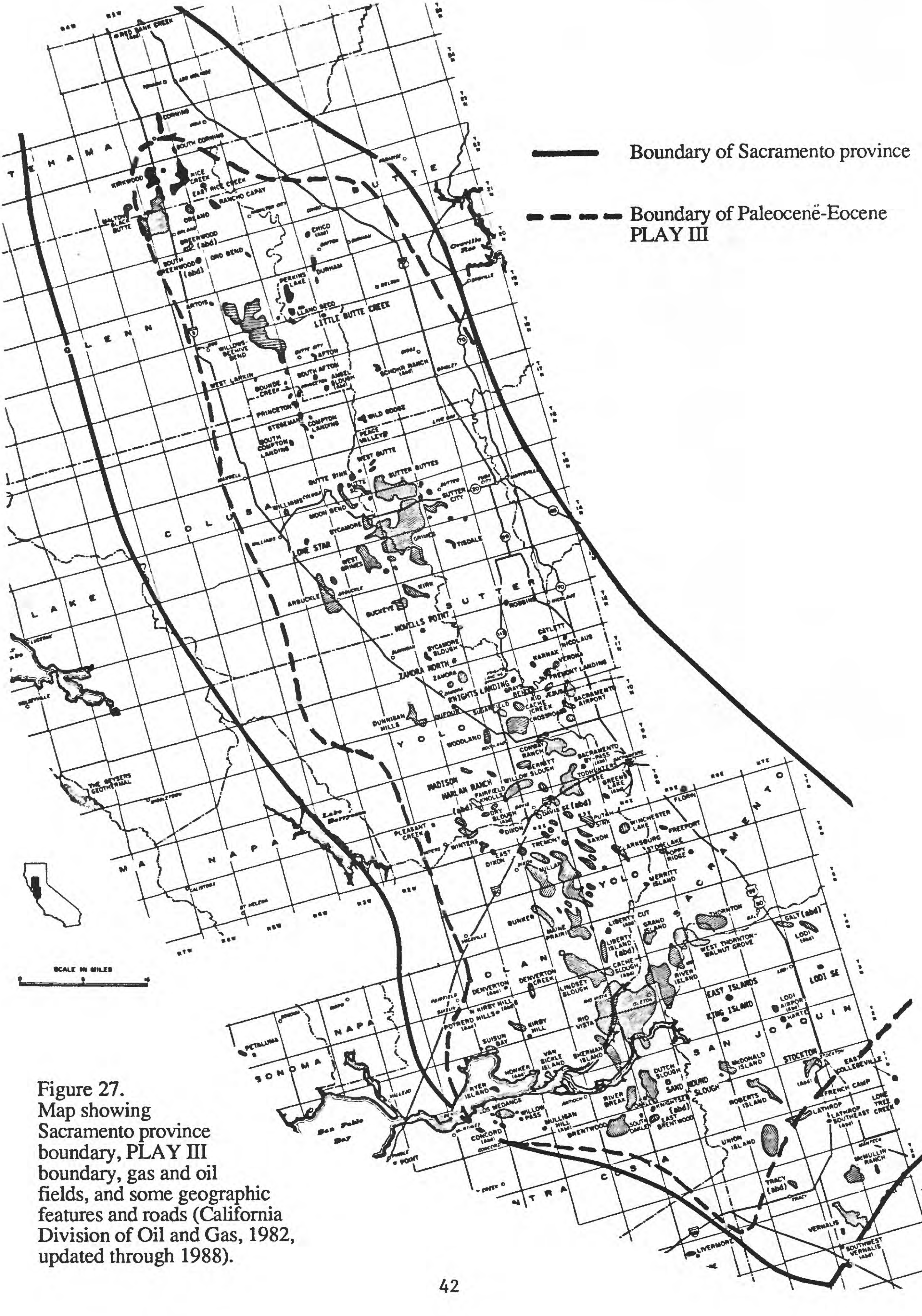

Figure 27. Map showing Sacramento province boundary, PLAY III boundary, gas and oil fields, and some geographic features and roads (California Division of Oil and Gas, 1982, updated through 1988).

Discovered accumulations in this play are negligible in terms of the total discovered gas in the Sacramento province but their occurrence is widespread (fig. 28). At the north end of the basin, "undifferentiated post-Eocene nonmarine rocks (probably "upper Princeton Valley fill") have yielded commercial quantities of gas in the Corning and South Corning fields. Moving southward, minor to noncommercial amounts of gas have been found in the Malton-Black Butte, Rancho Capay, Sycamore, Sacramento-By-Pass and West Thornton-Walnut Grove fields, as reported by the California Division of Oil and Gas (1982) (fig. 28). Non-commercial quantities of gas also have been found in the Sonoma Volcanics in the Suisun Bay field in the western Delta depocenter and in the Valley Springs-Mehrten formations in the Vernalis field at the south end of the province (fig. 28). Minor commercial quantities of gas also have been produced from Oligocene marine or fluvial sands in the Markley submarine canyon fill in the Verona, Greens Lake and Clarksburg fields (fig. 28). Many other occurrences of gas from post-Eocene rocks almost certainly have been noted by drillers but have not been tabulated by the California Division of Oil and Gas. Also, historical accounts describe gas production from wells originally drilled for water in the Stockton-Sacramento region (J. L. Sullivan, 1988, personal communication).

The source of gas in this play must be by migration from deeper reservoirs and source rocks, although shallow biogenic or microbial gas presumably contributes to some accumulations in the southern half of the province.

Because little is known about the internal post-Eocene stratigraphy of Sacramento basin (Graham, 1981), the likelihood of reservoir rocks, seals and the effects of late Cenozoic deformation (e.g., Harwood and Helley, 1987) are largely unknown. Past discoveries indicate, however, that the probability of significant undiscovered gas resources in this play is very low. Difficult-to-detect Oligocene sands within the fill of the upper Princeton valley and Markley submarine valley may offer the best prospects for future discoveries.

PETROLEUM DEVELOPMENT

The history of commercial petroleum exploration and production in the Sacramento basin, which dates back at least to the 1860's, began in earnest during the 1930's, and has been summarized in numerous publications (e.g., Stalder, 1943; Carlson, 1962; Franks and Lambert, 1985). Discovery dates, descriptions of gas and oil reservoirs and production data are available from various sources, but especially from publications and annual reports of the California Division of Oil and Gas, and the Conservations Committee of California Oil Producers. Only a brief summary of the petroleum development of the Sacramento basin is presented here.

Cumulative production and estimated reserves of natural gas, condensate and oil totaled nearly 9 Tcf of gas and more than 13 MMbbls of oil and condensate at the end of 1987. About nine-tenths of the discovered recoverable natural gas had been produced at the end of 1987 (Table 3).

The discovery rate of natural gas in the Sacramento basin is given in five-year increments in Table 4, along with individual fields with recoverable gas greater than 100 Bcf. While the discovery rate is reasonably good up through the early 1970's, less than 1.9% of the basin totals was discovered from 1975 through 1987 (fig. 29). MacKevett (1988) presented a very interesting summary of gas field discoveries in the Sacramento basin that included field-sized distributions, recoverable gas by field by year of discovery, and changes in predicted recoverable gas between 1951, 1976 and 1986 from pre-1951 fields. He concluded that between 1951 and 1986, the estimated recoverable gas from 27 fields discovered prior to 1951 increased by about 1.3 Tcf as a result of field development. Obviously, field development, as well as new field discovery rates, must be examined to make meaningful predictions about future gas resources of the Sacramento basin. Drilling activity from 1970 through 1988 is given in Table 5 (R. J. Bain, 1989, personal communication).

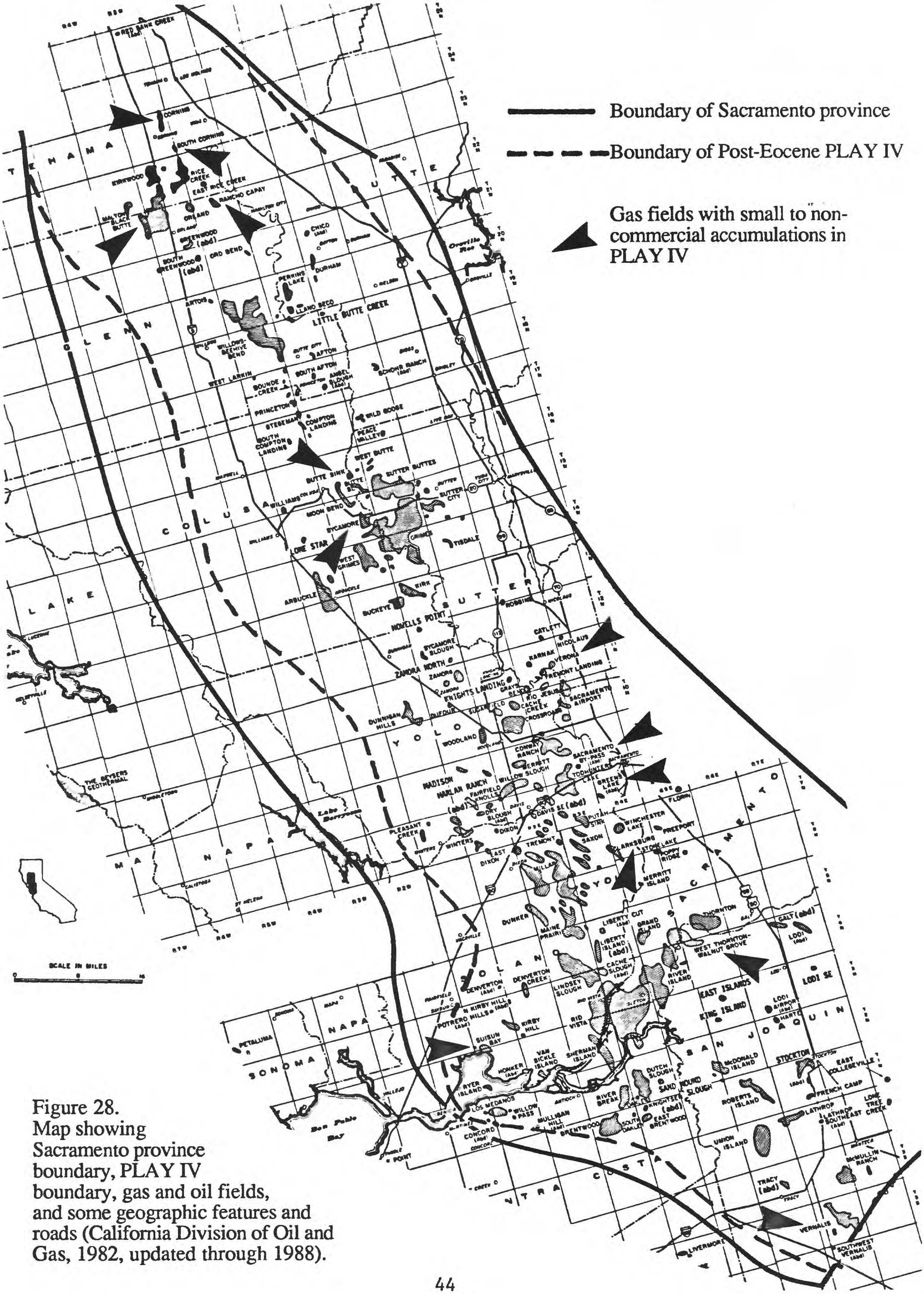

Figure 28.
Map showing Sacramento province boundary, PLAY IV boundary, gas and oil fields, and some geographic features and roads (California Division of Oil and Gas, 1982, updated through 1988).

Table 3. Cumulative production and estimated (discovered) reserves of natural gas and oil plus condensate in the Sacramento basin at the end of 1987, expressed in trillions of cubic feet (Tcf) and millions of barrels (MMbbls). Cumulative production and estimated reserves expressed as percent in right column. Figures are rounded off from California Division of Oil and Gas (1988).

Associated and nonassociated natural gas		
cumulative production	8.11Tcf	91%
estimated reserves	0.84	9
total	8.95	100
Oil and condensate		
cumulative production	12.71 MMbbls	96%
estimated reserves	0.56	4
total	13.27	100
Total natural gas, oil, condensate[1]		
cumulative production	1,364 MMbbls	91%
estimated reserves	141	9
total	1,505	100

[1]Natural gas is converted to energy-equivalent barrels of oil using 6 Mcf = 1 bbl. Expressed in gas units, total cumulative production plus estimated reserves of natural gas, condensate asnd oil is 9.03 Tcf.

Table 4. Recoverable gas of the Sacramento basin attributed to five-year periods of discovery. Data from California Division of Oil and Gas (1988) and the Conservation Committee of California Oil Producers (1988).

Five-Year Period of Discovery	Recoverable gas of new fields expressed as percent of recoverable gas of basin[a]		Fields discovered during period with recoverable gas greater than 100 Bcf (10^{10} ft^3)
1933 - 1934	2.1	(1)[b]	Sutter Buttes (187 Bcf)
1935 - 1939	45.5	(6)	McDonald Island (184 Bcf), Rio Vista (3,500 Bcf), Willows-Beehive Bend (377 Bcf)
1940 - 1944	5.7	(12)	Vernalis (101 Bcf), Millar (165 Bcf)
1945 - 1949	3.7	(8)	Maine Prairie (166 Bcf)
1950 - 1954	4.9	(11)	River Island (149 Bcf), Wild Goose (103 Bcf), Sutter City (111 Bcf)
1955 - 1959	4.6	(15)	Thorton West-Walnut Grove (118 Bcf)
1960 - 1964	22.4	(29)	Grimes (661 Bcf), Lathrop (358 Bcf), Lindsey Slough (279 Bcf), Dutch Slough (121 Bcf), Malton-Black Butte (133 Bcf)
1965 - 1969	4.1	(11)	Ryer Island (135 Bcf)
1970 - 1974	5.1	(12)	Union Island (262 Bcf)
1975 - 1979	1.6	(26)	--
1980 - 1984	0.2	(10)	--
1985 - 1987	0.1	(3)	--

[a]This column attributes all recoverable gas (as evaluated at end of 1987) to five-year period of discovery of first accumulation in field.
[b]Total number of gas fields discovered during five-year period.

Figure 29. Gas field discoveries from 1980 through 1988 as designated by the California Division of Oil and Gas. Knights Landing field was pending field designation at the end of 1988.

Table 5. Summary of well drilling and completion activity, gas production and well-head price of natural gas by year for period 1970-1988, Sacramento basin province. (R. J. Bain, 1989, personal communication). Based in part on information from Munger Oilgram and California Division of Oil and Gas.

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Number of holes drilled	122	126	141	155	180	164	153	155	163	156	228	238	214	234	270	241	148	174	159
Number of Redrills	10	11	25	20	30	43	19	15	18	11	32	35	26	29	20	21	12	16	13
Total number of holes drilled	132	137	166	175	210	207	172	170	181	167	260	273	240	263	290	262	160	190	172
Holes completed as Gas Wells	38	41	51	60	75	49	60	74	51	41	83	96	82	97	114	124	76	67	74
Success Percentage	29%	30%	31%	34%	36%	24%	34%	43%	31%	25%	31%	35%	38%	37%	39%	46%	48%	35%	43%
Number of Operators	42	47	48	47	41	44	44	56	56	53	63	56	68	58	65	72	46	56	41
Number drilled below 10,000 ft.	5	7	15	12	3	8	13	4	5	19	24	20	23	21	15	12	8	14	11
Deepest hole (000 Feet)	11.3	16.4	15.19	18.3	11.4	12.4	11.08	12.0	11.75	12.94	19.67*	12.8	14.1	13.2	11.8	12.52	16.8	12.2	10.9
Total gas produced - D.O.G. District 6 (Million MCF)	256	264	267	258	167	162	142	163	142	168	146	184	151	175	207	199	191	155	146±
Well-head Price (average)	30¢	33¢	35¢	39¢	44¢	60¢	98¢	$1.20	$1.45	$1.74	$2.04	$2.60	$3.14	$3.43	$3.72**	$2.94	$2.14	$1.69	$1.70

* Valley depth record
** Highest price = $3.85 - Dec. 1984

DISCUSSION

This report supported the 1987 petroleum assessment of the Sacramento basin by providing (1) a geological summary of the basin; (2) brief summaries of the thermal regime, source rocks, reservoir diagenesis and porosity, and petroleum development; and (3) definitions and descriptions of four petroleum plays used in the assessment procedure. Many excellent papers are published that provide more detail of the subjects summarized here (see References).

Petroleum play definition is a subjective process, and different workers may define, with equal validity, different plays based on different criteria. The criteria used here to define plays are given at the beginning of the PETROLEUM PLAYS section (p. 37). After play definition, the Nehring (1986) data base of estimated recoverable gas and oil from discovered gas and oil fields of the basin was allocated by play. Later steps in the petroleum assessment procedures are beyond the purview of this report, and the reader is referred to Houghton (1987), Crovelli (1988), and Mast and others (1988).

Estimated recoverable gas from discovered accumulations through 1987 is given by play in Table 6, with and without inclusion of the large Rio Vista gas field. Table 6 shows that, when Rio Vista is included, Paleocene and younger rocks contain half of the discovered gas and approximately one-quarter each is in the Starkey-Winters-Mokelumne River (and equivalents) and the Kione-Forbes (and older rocks). Exclusion of the Rio Vista field dramatically changes the proportions with Paleocene and younger rocks accounting for only one-fifth of the discovered gas whereas Starkey-Winters-Mokelumne River and Kione-Forbes each contain about two-fifths of the total discovered recoverable gas in the basin, based on data of the California Division of Oil and Gas (1988).

The history of gas discoveries in the Sacramento basin province has been controlled largely by advances in exploration technology (e.g., Nahama and Weagant, 1972; Moser and others, 1986; Morgan and Campion, 1987; Vuillermoz and others, 1987; Weagant and Sterling, 1987, 1989) and by economic forces (e.g., Morrison and others, 1971; Lippitt, 1987). While economic factors are beyond the subject of this report, continued progress in geophysical exploration methods, espe-cially seismic methods, and the continued application of modern sedimentological concepts, espe-cially the recognition in the subsurface of depositional environments and sediment packages, will be crucial to new petroleum discoveries. While the continued discovery of relatively small gas reservoirs (pools) and fields seems assured if the economic climate is favorable, discovery of relatively large gas accumulations is more problematical.

Today much of the unexplored portion of the Sacramento basin is at greater depth in the Delta depocenter where few deep wells have been drilled. There are reasons to doubt that significant gas resources lie at greater depths in the basin, but the potential can be investigated. Areas that require better understanding include:

(a) thermal and pore-fluid pressure history of different parts of the basin and their effect on gas migration and reservoiring, and on sandstone porosity and permeability

(b) further organic geochemical studies, building on the results of Jenden and Kaplan (1989), to better understand the sources of gas produced from the basin.

(c) deep crustal exploration with specialized seismic experiments to unravel the deeper structure of the basin and underlying basement

Table 6. Estimated gas by petroleum play expressed as percent of estimated discovered recoverable natural gas in Sacramento basin, including and excluding the Rio Vista gas field. Cumulative production and estimated reserves as of the end of 1987 (California Division of Oil and Gas, 1988).

		Cumulative natural gas production plus estimated reserves expressed as percent of basin total	
	Petroleum Play	with Rio Vista	without Rio Vista
I:	Post-Eocene	0.2%	0.3%
II:	Paleocene-Eocene	49%	19%
III:	Starkey-Winters-Mokelumne River and Equivalents	27%	42%
IV:	Kione-Forbes and Pre-Forbes	23%	38%

ACKNOWLEDGEMENTS

The author wishes to thank Norman (Toby) Scott III who, while working at the Geological Survey, initially defined the petroleum plays and wrote preliminary descriptions of them. The author is also grateful to John C. Sullivan (California Division of Oil and Gas), Miles W. Pepper (Pepper and Kittredge Exploration), Robert G. Lindblom and Edward von Dohlen (Chevron USA, Inc.), Jack H. West (Occidental Exploration and Production Co.), and David S. Harwood (U.S. Geological Survey), for useful discussions. Table 5 was kindly provided by R. J. Bain.

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